The University of Chicago

SUBTROPICAL FLOW PATTERNS IN SUMMER

A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF METEOROLOGY
1947

By
HERBERT RIEHL

Reprint of
Miscellaneous Report No. 22
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I. INTRODUCTION [1]

The problems of weather analysis that exist within the zone of the deep tropical easterlies give way on the equatorward side of the easterlies to questions concerning the interaction between the subtropical highs and the tropical currents of both hemispheres. At the poleward boundary of the tropical current problems arise due to the ever changing relation between this current and the disturbances in the polar westerlies.

This report deals with some of the summertime forecasting problems of the southern United States, a region well within the subtropical belt during summer. The reason for writing the paper was a desire on the part of the United States Weather Bureau for further studies of thunderstorm situations in summer along the Gulf Coast, since the exclusive use of energy diagrams and frontal analysis was not entirely satisfactory for forecasting. Several writers, especially Namias (3), have pointed out previously that the breakdown of the thunderstorms into air-mass and frontal types is inadequate and that the factors which have a bearing on thunderstorm formation are frequently not evident on the surface chart. For this reason a detailed analysis of the upper air, especially of the continuous changes that result from the interaction between the two major zonal currents, form the basis for this study. Although a complete interpretation of all thunderstorm cases was not to be expected, the material which follows may nevertheless prove of some assistance to forecasters in the subtropics.

The author wishes to express his thanks to the United States Weather Bureau and Dr. Charles F. Sarle, assistant chief for scientific services, for sponsoring the project; to Dr. Horace R. Byers and Mr. Lynn L. Means for many hours spent with him in discussion of the material; and to Messrs. Charles Gilman, George P. Cressman, and Dave Fultz for many suggestions on the revision of the manuscript.

Note on maps.--Only situations with sufficient upper-wind data are reproduced. Most of them, therefore, do not represent extreme weather conditions. Depending on the density of upper-wind reports and the rapidity of synoptic changes, successive maps are sometimes 24 and sometimes 12 hours apart.

The streamlines are drawn parallel to the wind direction but do not represent the wind speed. If the wind arrows had been plotted, it would not have been possible to superpose the upper pattern on the surface isobars. As

[1] Manuscript submitted May, 1945.

it is one of the aims of the report to demonstrate the relation between upper and lower flow in the subtropics, the superposition was retained and the wind arrows were sacrificed. The reader can obtain them by reference to back files of data.

Current weather, cumulonimbus clouds, and thunderstorms during the last 6 hours were entered on the charts approximately up to Latitude 40° N and Longitude 100° W. In looking over the maps, it should be remembered that the illustrations represent different times of the day and that the diurnal effects vary greatly. In addition, the spotty character of the thunderstorm activity is notorious, so that it is often very difficult to obtain a fair picture of organized convection zones as compared with scattered diurnal showers.

Past thunderstorms are represented by the symbol ⌇ .

1. Working Procedure and Materials

An analysis of thunderstorm situations with use of days with thunderstorm occurrence only is often not conclusive. The same factors which appear to account for the convective activity on some days may also be present on others which remain free of thunderstorms. To avoid this difficulty, the study covers all the summer days and not just thunderstorm days. Three summers--June to September of 1940, 1941, and 1943--were studied to make reasonably sure that most of the important weather sequences were included.

The charts used included surface maps and upper-wind and isobaric charts. For certain critical days isentropic charts were prepared. Computations from United States Weather Bureau Forms No. 1109 for stations in the southern and central parts of the United States supplemented the analysis. These computations included 24-hour changes of pressure, temperature, and humidity at 1.5 km, 3 km, and 5 km, and calculations of the lapse rate from the surface to 1.5 km, from 1.5 km to 3 km, and from 3 km to 5 km. Humidity values at 1.5 km, 3 km, and 5 km were also tabulated. Plotted soundings gave the necessary information on inversions between the fixed levels.

The United States Weather Bureau furnished airway observation forms for numerous southern stations, which served as the basis for a detailed tabulation of thunderstorm data. This tabulation was restricted to the middle and west Gulf stations to keep the work within reasonable limits. The results in general, however, may be applied to the Atlantic Coast as well as to any other subtropical region placed similarly with respect to the general circulation, with allowance for varying local conditions.

TABLE 1

FREQUENCY OF THUNDERSTORM DAYS FOR THREE SUMMERS

Year	GS	HU	FV	ZH	NO	VS
1940.....	47	43	36	29	59	27
1941.....	52	68	57	50	81	45
1943.....	40	53	26	37	63	40
Total...	139	164	119	116	203	112

2. Thunderstorm Frequency and Distribution

A breakdown of the thunderstorm activity at Galveston, Texas (GS), Houston, Texas (HU), Fort Worth, Texas (FV), Shreveport, Louisiana (ZH), New Orleans, Louisiana (NO) and Vicksburg, Mississippi (VS), appears in Tables 1 and 2. The variability of the number of thunderstorm days from year to year is large (Table 1). New Orleans and Houston have the highest totals over the whole period, and the amounts for all stations, except Vicksburg far exceed those given by climatology, owing to the following circumstances:

1. The airways data are taken on a 24-hour basis, while the climatological summaries represent mainly observations preceding the airways era.

2. This report deals with synoptic patterns and not merely with thunderstorm occurrences at given stations. Therefore, distant lightning and reports of thunderstorms in the vicinity of the stations were included.

The seasonal trend of thunderstorm frequency is brought out in Table 2. The convective activity is highest in July and August at most stations, while Fort Worth has a June maximum in agreement with climatological data. The Galveston figures, however, do not reflect the trend toward diminished midsummer rain.

TABLE 2

FREQUENCY OF THUNDERSTORM DAYS FOR THREE JUNES, JULYS, AUGUSTS, and SEPTEMBERS

Months	GS	HU	FV	ZH	NO	VS
3 Junes.....	35	47	43	33	53	29
3 Julys.....	43	51	25	37	69	45
3 Augusts.....	34	39	31	30	54	27
3 Septembers.....	27	27	20	16	27	11

TABLE 3

PERCENTAGE FREQUENCY OF THUNDERSTORM OCCURRENCE
AT DIFFERENT TIMES OF THE DAY

Time	GS	HU	FV	ZH	NO	VS
A.M.	22	13	15	7	14	5
P.M.	27	39	23	42	43	50
Night.....	51	48	62	51	43	45

In order to ascertain the diurnal variation of thunderstorm frequency, the days were divided arbitrarily into three unequal parts: morning, from 6:00 A.M. to noon; afternoon from noon to 7:00-8:00 P.M.; and night (Table 3). Except for Vicksburg, the nighttime thunderstorms constitute the largest group at all stations and account for more than half of all thunderstorm periods at several stations. This relation between daytime and nighttime thunderstorms holds up well in many individual months.

Unfortunately, Table 3 is not wholly representative, although it certainly emphasizes the great importance of nighttime thunderstorms. Distant lightning is mainly visible at night. Moreover, most of the stations are located in areas with considerable nighttime activity due to topography or proximity of the sea. In spite of these local influences, the distant lightning followed the synoptic situations to a considerable degree, and it is therefore of importance for this study.

It should never be overlooked, however, that the periodic changes tend to overshadow the aperiodic changes of weather with decreasing latitude and that local conditions uphold the diurnal maximum whenever possible. Except for a narrow coastal strip, the daytime heating in the south shifts the periodic thunderstorm activity toward the hours of high surface temperatures. Organized convection zones connected with specific disturbances thus will tend to widen considerably in the afternoon and shrink or even disappear in the early morning hours.

The radiative activity usually will even suffice to overcome some velocity divergence, especially in southerly and southwesterly currents. This is not altogether surprising, since there is not necessarily a close correlation between the field of instantaneous divergence and the occurrence of cumulonimbus. Low-level divergence, operating on an air column for some time, will surely reduce that column's ability to produce thunderstorms. When divergence first becomes effective, however, the column may very easily retain a thermo-

dynamic structure for some time that will permit it to respond to the diurnal heating with thunderstorms.

Scattered afternoon thundershowers are particularly frequent when the circulation aloft is very light and when there is no general tendency for the air either to rise or to subside. Such conditions may be attained even in the subtropical ridgeline itself. Thunderstorms break out on the first afternoon following establishment of the weak circulation if there is an initial high moisture content of the air Otherwise the thundershowers begin on the second or third day when the upper air has had an opportunity to increase its moisture through vertical mixing.

II. THE MEAN SEASONAL CIRCULATION

1. The Average Flow Pattern in Summer

The summer rainfall along the Gulf Coast is largely dependent on the seasonal circulation pattern aloft, as given by the position of the mean subtropical cols, polar troughs, and the subtropical highs that flank them. In midsummer the West Atlantic polar trough extends from the Atlantic southwestward into the Gulf of Mexico (Fig. 1), and the subtropical col lies over northern Florida, Georgia, and Alabama.

The easterly current that arrives from the Atlantic and the Caribbean does not cross the polar trough as a body but splits. One part curves anticyclonically into the higher latitudes; another portion passes through the trough in the south turning toward Central America. Between these two branches subsidence tends to develop in the southeasterly drift over the central and west Gulf as shown by the decrease of precipitation from Central America northward toward Brownsville, where the average July and August rainfall is only about 4.6 inches.

The tropical air which moves into the higher latitudes east of the polar trough theoretically (7) needs neither to converge nor to diverge. But a large variety of situations arises--the object of the later discussion--which do produce convergence in this current, raising the average depth of the moist layer as compared with the undisturbed easterly current. After passing Latitude 30° the current possesses thermal and moisture properties distinct from other summertime air masses over the southern United States. Local changes of temperature and moisture due to advection will therefore occur where this current replaces other air masses in the subtropics.

The mean polar trough is reflected on the average summer isentropic chart (3). The warm tongue in the Southeast represents the air current east of the troughline. In the southwestern United States another warm tongue appears east of the East Pacific polar trough. The air with the highest moisture content in the Southeast lies somewhat west of the valley in the isentropic surface and straddles the polar trough just north of the col. The convection extends to at least 100 miles west of the troughline, and a gradual transition from bad to good weather occurs. In the western United States, however, the moist tongue over the mountains lies far to the east of the warmest region. Very dry air derived from the East Pacific High moves through the polar trough located off the Pacific Coast. This current needs to travel

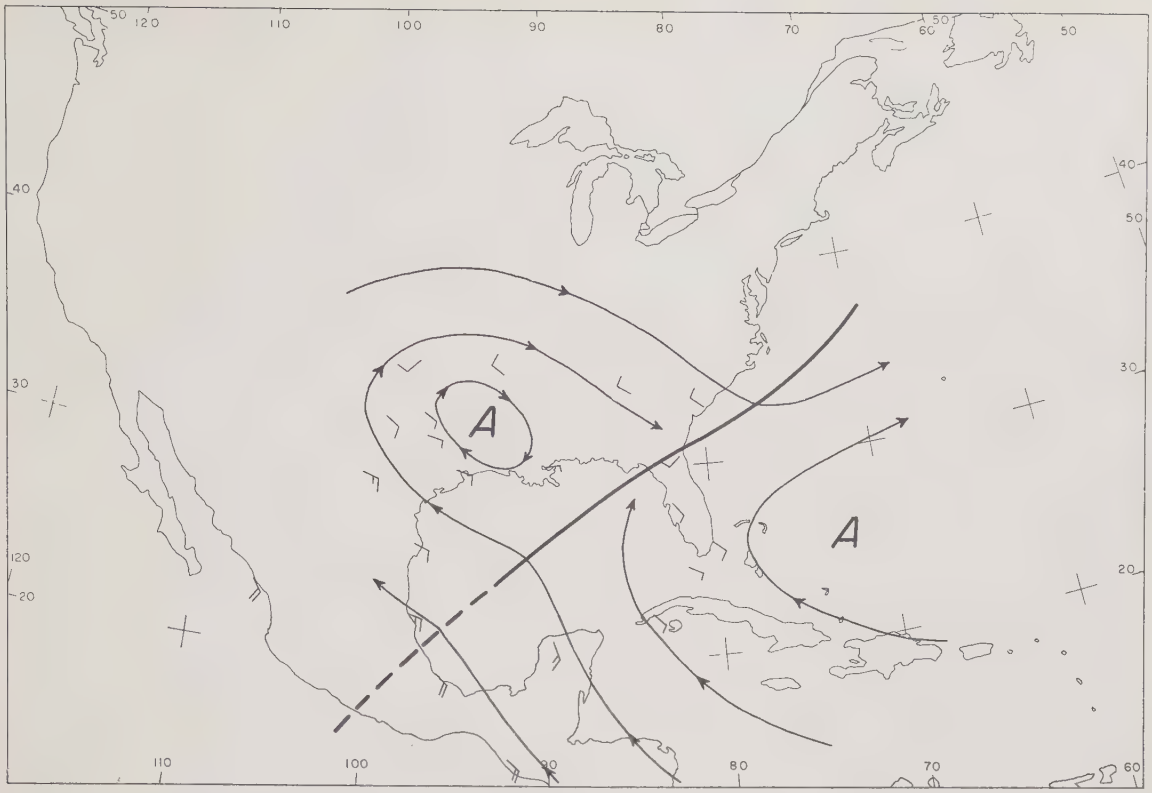

FIG. 1.--Mean August circulation at 10,000-12,000 feet over the southern United States and along the Gulf of Mexico. The wind vectors were obtained from upper-wind summaries of the United States Weather Bureau and Pan American Airways, Inc. In this and the following drawings the A stands for anticyclonic circulation and the C for cyclonic circulation.

considerable distances eastward from the troughline, before mixing with other currents from the lower latitudes leads to a pronounced increase of its humidity.

2. The Seasonal Shift of the Mean Trough

In the colder season the West Atlantic polar trough lies mostly east of the 80th-85th meridians in the subtropics and tropics. As the activity in the belt of polar westerlies diminishes rapidly in May and June, the Florida winds aloft back to southwest, and a trough begins to appear in the Gulf. Coincident with this shift of the winds, the summer thunderstorms start over the Florida peninsula after the pronounced dry spell ordinarily experienced in spring. At the same time convection at the southern Texas coast begins to lessen.

The reverse windshift from southeast and southwest to northwest takes place over Florida in the second half of September and during October, when the continent cools and the westerly circulation increases. This event coincides with the conclusion of the main rainy season in Florida, while the southern Texas coast experiences a second maximum of precipitation.

The hurricane frequency in the western Caribbean and East Pacific follows closely this seasonal migration of the mean polar trough. Tropical storms in the western Caribbean and the East Pacific originate primarily near points of juncture between polar troughs and the equatorial front. These "triple points" tend to lie in the southern Caribbean in May and June, when the equatorial front first becomes active. In midsummer and early fall they appear with greatest frequency in the East Pacific off the Central American Coast, in agreement with the seasonal shift of the mean polar trough. The western Caribbean, therefore, has only a brief hurricane season in late May and early June, and the formation of tropical storms there is most uncommon in midsummer. In the East Pacific, however, the activity starts in July and reaches its maximum in late summer.

As the mean triple point reappears in the western Caribbean in the fall, hurricane activity resumes there during the second half of September and attains its annual maximum in the first half of October.

III. THE BROAD SCALE WEATHER SITUATION

1. Classification of Major Flow Patterns

Because of the marginal position of the subtropics between the easterlies and the westerlies, a great variety of major recurrent flow patterns appears there. The subtropical zone sometimes participates in the westerly circulation of the north and at other times in the easterly circulation of the south. If one refers to the periods when the middle latitudes dominate the subtropical weather as "polar days" and those with predominantly easterly flow aloft as "tropical days," then the Gulf Coast--except Florida and the southern tip of Texas--experienced 235 polar days during the summers of 1940, 1941, and 1943, 86 tropical days, and 40 other days, mostly intermediate in nature characterized by the presence of a closed low aloft near the coast. The ratio of polar to tropical days depends, of course, somewhat on the particular summers analyzed. It is probable, however, that an extension of the study over a longer period would not result in any material alteration of the ratio.

Table 4 indicates the percentage of all thunderstorm days that occurred during the polar and tropical regimes at each of the stations analyzed in detail and, similarly, the percentage of all days without precipitation. It is evident that both the largest number of dry days and the majority of thunderstorm days fall within periods dominated by the southern margin of middle latitude disturbances.

As brought out by Table 5, however, the polar days are relatively drier than the tropical days, especially at the coastal stations. The relative thunderstorm frequency is greater during the tropical days but, except at Galveston, only slightly. Days with rain but without thunderstorms account for the balance of the percentages in this table.

The general classifications "polar" and "tropical" days can be subdivided further, according to the most important features that characterized the flow pattern of each day. For this purpose the upper flow has to be utilized, primarily because the surface chart in summer only rarely indicates distinctly what goes on in the atmosphere. When a pronounced pattern does appear on the surface, the time for a forecast has usually passed.

The classification which follows suffers from the defects common to most such attempts. It is impossible to include all the features of any given day, unless each day is to receive a separate name. In addition, the various

TABLE 4

PERCENTAGE FREQUENCY OF THUNDERSTORM DAYS AND OF DAYS WITHOUT PRECIPITATION DURING POLAR AND TROPICAL REGIMES, REFERRED TO TOTAL NUMBER OF THUNDERSTORM DAYS AND TO TOTAL NUMBER OF DAYS WITHOUT PRECIPITATION

Type	GS	HU	FV	ZH	NO	VS
Thunderstorm days:						
Polar regime.....	51	56	61	62	63	59
Tropical regime.....	35	31	25	27	26	29
Days without precipitation:						
Polar regime.....	77	80	65	70	79	68
Tropical regime.....	10	10	24	20	13	23

TABLE 5

PERCENTAGE FREQUENCY (TO NEAREST 5 PER CENT) OF THUNDERSTORM DAYS AND OF DAYS WITHOUT PRECIPITATION DURING POLAR AND TROPICAL REGIMES, REFERRED TO TOTAL NUMBER OF DAYS IN EACH REGIME

Type	GS	HU	FV	ZH	NO	VS
Polar regime:						
Thunderstorm days.....	30	40	30	30	50	30
Days without precipitation	55	60	30	35	60	40
Tropical regime:						
Thunderstorm days.....	60	50	60	60	40	60
Days without precipitation	25	20	55	50	15	55

subdivisions overlap. The synoptic systems of the subtropics in summer often are of small dimensions, and several quite diverse disturbances may appear simultaneously on some occasions.

Among the polar days, the following principal patterns could be distinguished:

a) A large-scale upper trough extends from the Atlantic across the southeastern United States into the Gulf of Mexico.

b) A large-scale upper trough lies near the Mississippi Basin.

c) There is no large-scale trough east of the Rockies. Smaller waves in the westerlies pass through the northern United States.

d) Well-developed polar fronts affect the Gulf Coast.

The tropical days would be subdivided as follows:

a) Waves in the easterlies pass along the Gulf Coast.

b) The subtropical highs are arranged N-S rather than E-W, and a shearline oriented approximately E-W to NE-SW lies near the Gulf Coast.

c) A tropical storm is present.

2. Brief Description of Several Patterns

a) If an upper trough, for instance at 15,000 feet, extends from the western Atlantic to the Gulf of Mexico, the situation resembles closely the mean seasonal map of Figure 1. Smaller waves in the easterlies and westerlies move toward the broadscale trough, and its amplitude and area of bad weather increase when the smaller waves merge with it. Small to moderate surface low centers usually accompany the waves in the polar westerlies eastward in conjunction with cold fronts, which, however, rarely penetrate south of Latitude 35°.

The subtropical col at upper levels lies variably between Alabama and the Bahamas. A weak col also appears occasionally in the surface pressure field. More frequently, however, there are southwesterly isobars with some anticyclonic curvature and a flat gradient, representing the western limit of the surface Bermuda High.

The moisture distribution tends to correspond to that shown on the average isentropic charts. Convection is active to very active along the eastern Gulf Coast and over New Mexico and Arizona, while dryness prevails over Texas and most of Louisiana.

b) If a large-scale upper trough lies near the Mississippi Basin (Fig. 2), it extends to Central America either east or west of the Texas coast. The subtropical col is located over the central and western Gulf, occasionally advancing north of the coast line. The amplitude of the upper windfield tends to be large, and the subtropical highs may appear 5°-10° latitude farther north than drawn in Figure 1.

Waves in the easterlies now have a chance to penetrate farther west in the southern United States. Smaller waves in the polar westerlies move with pronounced meridional components. They generally enter the North American weather map from Alaska and drift in the broad northwesterly current toward the large-scale trough. After passing it, they move northeastward in the southwesterly current ahead of the main troughline. Because of this change of direction of movement these smaller perturbations have recently been labeled "NW trough" and "SW trough," respectively, by Fultz (2).

Moderate to deep surface low centers progress into northeastern Canada

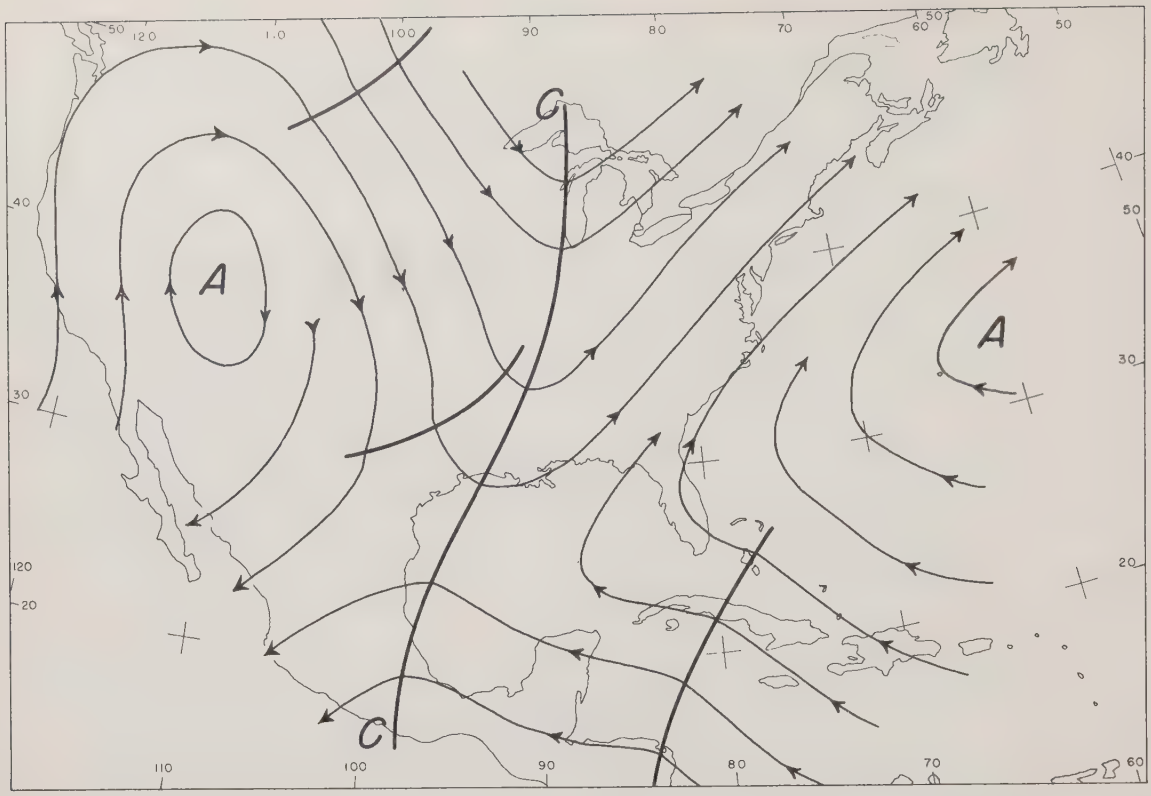

FIG. 2.--Typical picture of the flow between 10,000 and 15,000 feet when the mean polar trough lies near the Mississippi Basin.

during such periods, and, because of the considerable northerly component of the upper flow west of the Mississippi, their cold fronts can reach the central and west Gulf Coast. Many times, however, the surface fronts stagnate near Oklahoma City and even farther north.

c) In the absence of well-marked large-scale troughs and ridges, the polar westerlies exhibit a great variety of patterns, depending on the strength and latitude of the principal west-wind belt. If the upper winds are strong and almost due west, the map resembles the high index situations of winter; the subtropical ridgeline, elongated E-W and without pronounced cols, lies near the coast line. Waves in the westerlies are barely perceptible south of Latitude 35°.

More often, however, the winds are from the southwest over the central and west Gulf area, while an upper high is centered over the Carolinas or just off the East Coast. Waves in the westerlies which arrive from the Rockies then have sufficient strength to be active in the south just east

of the mountains. From the eastern slopes of the Rockies they either travel northeastward as SW troughs, or their northern and southern parts split. The high latitude section proceeds to the Atlantic, while the low latitude portion remains blocked in the Southwest. Occasionally a stagnant large-scale trough overlies the Rockies, from which the smaller disturbances pass eastward.

On the surface map a well-marked lee-of-the-mountains trough persists under these circumstances, with good southerly flow and hot weather to the east of it. Surface frontal analysis is uncertain and difficult. On many days a seemingly sharply defined cold front starts out eastward from Colorado and Oklahoma, only to become completely indistinct 12 hours later. Numerous surface low centers form in the western Plains States. Only a few of these, however, are able to proceed northeastward across the continent.

Convective activity precedes most of the moving troughs and tends to be very active in Oklahoma and northern Texas with lessening intensity southward. The bulk of the Gulf Coast experiences scattered thunderstorms due to diurnal convection in a weak field of motion.

d) Active frontal zones reach the coast mainly in connection with the eastward passage of a large-scale trough. While the upper trough is situated west of the fronts in the higher latitudes, it nearly always precedes the front in the south, a fact previously stressed by the author (6). The point at which front and upper trough cross usually lies 2°-5° latitude north of the coast in summer. South of this point the greatest thermodynamic instability necessarily prevails east of the front.

The cold fronts which reach the coast from the northwest rarely come from Canada but tend to form along the eastern edge of the mountains as the trough aloft passes over that region. Fronts from eastern Canada, however, frequently move down the Atlantic seaboard with an E-W orientation that may even change to SE-NW as the front approaches the Gulf Coast.

e) Waves in the easterlies appear when activity in the belt of polar westerlies has ceased in the middle latitudes and when a warm anticyclone overlies the central and eastern United States. Easterly winds--occasionally extending to 13 km and beyond--then blow along the entire Gulf Coast; waves proceed westward in this easterly current as in the trade-wind belt.

Such a situation, however, rarely persists even for 48 hours. The West Atlantic and East Pacific polar troughs are very far apart under such circumstances, and there is a persistent tendency for the Atlantic trough to retrograde and to reduce the eastern portions of the high. At the same time the Pacific trough seeks to enter the continent from the west.

Since the pattern is usually short lived, especially in the west Gulf

region, waves that reach Florida from the east are rarely able to advance all the way to Texas. Their frequency of appearance thus decreases from east to west. Usually they either dissipate on their way westward or consolidate with a trough in the polar westerlies. Some waves, however, which pass from the Caribbean into the southern part of the Gulf reach Texas with the general southeasterly drift near the Central American coast, predominantly in a state of dissolution.

f) When a closed upper high overlies the central United States, the easterlies on the south side of this high rarely extend uniformly to the equatorial zone. A second anticyclone commonly is located over the Gulf or the western Caribbean almost south of the center over the United States, and between these two highs there is an upper shearline that is oriented NE-SW to E-W (Fig. 3). The separate highs and the intermediate shearlines--although common on upper-air charts--are noticeable on the surface chart only in rare cases.

The cyclonic windshear in the middle troposphere between the two upper highs is very pronounced and often amounts to almost 180°. Thus, the field of motion is very favorable for cyclogenesis. Indeed, the presence of one or more small upper vortices along the shearline may be counted on almost regularly. These vortices are likely to become unstable and rapidly produce a cyclonic circulation aloft around the entire Gulf area. Hurricane formation may result.

Although active convection takes place on both sides of the the shearline, it often is more vigorous in the tropical current on the southern side. During a northward advance of a shearline into the southern United States, the weather may rapidly deteriorate along the entire Gulf Coast simultaneously. About 200 miles north of the line the superior air flowing from the warm high in the United States tends to cut off convection.

3. Seasonal and Monthly Distribution of Patterns

Although each of the patterns just described occurred in every one of the three summers studies (Table 6), the forecaster cannot rely on any specific number of days of each group in any given year. This is not surprising. The great variability of hurricane frequency from one year to the next, for instance, is well known. Similarly, the polar westerlies maintain themselves in the southern United States almost throughout the whole summer in some years, while in others the activity in the polar belt fails for long periods, and the easterlies have a chance to dominate the United States.

As should be expected from the mean seasonal picture, stagnation of a

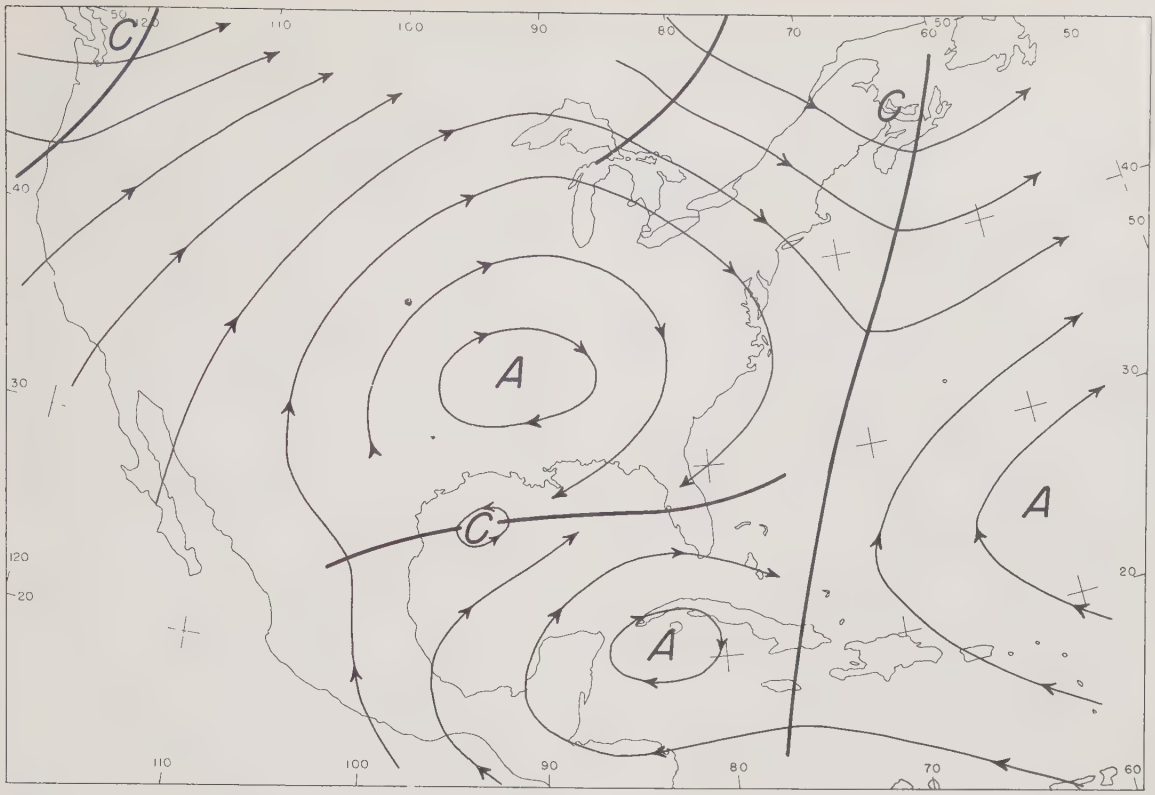

FIG. 3.--Typical picture of the flow between 10,000 and 15,000 feet when an east-west shearline lies over the Gulf of Mexico.

polar trough near the East Coast is a preferred pattern. A summertime position near the Mississippi Basin is far less common. The largest number of days, by a very small margin, was characterized by the westerly patterns which include a large variety of weather sequences. The third largest group, surprisingly enough, consists of "frontal days" in contrast with the statement often heard, that fronts rarely affect the Gulf Coast in summer. In this connection the author desires to emphasize that he carried out the frontal analysis along the most conservative lines. Only boundaries eligible for the name "front" in the strict Norwegian sense were thus labeled.

It is of interest to see in what order the various groups succeeded each other. In Table 7 the 24-hour succession of types is given, using all three summers. The horizontal columns represent the number of times the group listed under "Before" changed to the group entered under "After." The vertical columns give the reverse. Addition of the vertical and horizontal columns does not check out entirely because there were a few missing days.

The persistence column, inclosed by the diagonals, has by far the largest figures. Particular persistence is evidenced by the trough in its mean posi-

TABLE 6

FREQUENCY (IN DAYS) OF EACH PATTERN

Pattern	1940	1941	1943	Total
Polar trough near East Coast	25	9	43	77
Polar trough near Mississippi Basin	6	13	12	31
Westerly patterns.....	13	39	28	80
Active front.....	17	22	8	47
Wave in the easterlies.....	14	14	5	33
East-west shearline.....	5	5	14	24
Hurricane.....	5	15	9	29
Closed upper low.....	23	2	2	27

TABLE 7

24-HOUR SUCCESSION OF PATTERNS

BEFORE \ AFTER	Polar Trough near East Coast	Polar trough near Mississippi Basin	Westerly Pattern	Active Front	Wave in the East-erlies	East-West Shear-line	Hurricane	Closed Upper Low
Polar trough near East Coast.....	52	4	3		6	4	1	
Polar trough near Mississippi Basin..	6	24	2	2	3	1	1	
Westerly pattern.....	2	1	54	14	1	1		3
Active front.....	4	8	5	28	1	1		1
Wave in the easterlies	2		2	1	20	1	5	1
East-west shearline...			7			17		1
Hurricane.....			1	2	1		22	3
Closed upper low	2	1	1	3	1			18

tion--with an average change of once in 4 days--the westerly patterns, and hurricanes. This is reasonable. The slow movement of most hurricanes is well known, and the other two groups represent stable patterns from the broad scale viewpoint. Frontal days have least persistence and rarely predominate for more than two consecutive days. They represent transition periods in summer. The flow of polar air southward rarely lasts long and its modification is rapid.

4. Some Suggestions on Forecasting the Broad Scale Patterns

In order to forecast in the subtropics, it is necessary to analyze a map extending far to the east and west of the forecast district. The importance of synoptic conditions to the east, first stressed for the United States by Namias (4), cannot be overemphasized. For instance, a polar trough currently stationary near the Atlantic seaboard will tend to start moving eastward not only at the approach of another trough from the west; it will also react to changes of position and intensity of troughs and ridges to its east. It was, for instance, stated by the author (6) that a surface high may be referred to as a "blocking" high, using the terminology of Namias (4), if an upper anticyclone is located over the surface center and the slope of the base of the polar westerlies tends toward the vertical. The streamline amplitude is then large and maintains itself with elevation. The troughs on either side of the high will stagnate. If, however, the streamline amplitude decreases with height and the upper high lies well to the south of the surface high, the troughs will be carried eastward in the upper westerlies and the surface high must give way southward.

The presence of a pronounced trough or ridge in the middle troposphere, with westerly winds on either side, represents an unsteady state, which must lead either to a disappearance of the upper system or to an increase in amplitude of the entire field. Many times a closed low aloft reaches the Rocky Mountain area from the Pacific, while west winds prevail over the bulk of the United States. This low will diminish in intensity and accelerate eastward, if additional waves follow it from the west. If, however, the East Pacific high has spread far north to the rear of the low and the streamline amplitude is large in the East Pacific Ocean, then the low tends to stagnate over the Rockies, and the winds along the east coast will veer from west to northwest.

Conversely, suppose that a trough enters the continent from the west while in the east there is a pronounced trough in the mean position, similar to Figure 1, with a strong Bermuda High and a steep base of the westerlies in the western Atlantic. If the western trough is followed by the East Pacific cell, upper winds along the entire Pacific Coast will turn to northwest

and north, and very unsettled weather can be expected for several days over the larger part of the United States. The streamline amplitude will be very large, with two major troughs over the continent which stagnate completely or move very slowly. Deepening with the development of closed upper lows in both troughlines is likely to follow.

If, however, smaller disturbances in the westerlies follow the first Pacific trough, the latter will damp out and reach the area east of the Rockies as a SW trough. Simultaneously, the next trough to its west will deepen near the mean position of the east Pacific trough, as upper winds along the West Coast back from west to southwest and south. Except for the fact that the first perturbation can be traced eastward, often across the whole continent, one might speak of a retrogression. An analogous sequence takes place in the eastern United States, when an apparent retrogression of the East Coast trough to the Mississippi Basin occurs.

Transition from polar to tropical pattern.--If a major trough stagnates at the East Coast, while activity in the polar belt over the East Pacific and the western United States weakens or ceases entirely, a closed anticyclone aloft will soon develop in the central part of the United States, often located as far north as Illinois. The transition from a polar into a tropical map is only infrequently accomplished through a gradual advance of the tropical easterlies and the subtropical ridgeline northward. In most cases the subtropical ridgeline remains quasi-stationary or moves northward but slowly, while a new set of easterlies develops far to its north. These easterlies are initially observed between approximately 10,000 and 15,000 feet. Subsequently they spread both upward and downward in the atmosphere. Although the new anticyclone forms with preference over modified polar air-- in agreement with Wexler (8)--it will appear whenever there is stagnation at the East Coast and the wind speed in the belt of westerlies lightens.

A narrow zone of strong cyclonic shear develops in the middle troposphere between the newly formed anticyclone and the old subtropical ridge, a site of frequent thunderstorms. While the polar belt remains inactive, the two highs rarely merge and retain their N-S arrangement. Occasionally, the northern high grows to large proportions, with easterly winds in the middle troposphere covering the eastern and central United States at Latitude 40° N. and at times even at Latitutde 45°N.

Resumption of the westerly flow east or west of the northern high will cause it to vanish, if it is still in its early stages of development. If, however, it has become well established and extends through a large portion of the troposphere, it will merely be pressed southward. The shearline between the two warm highs then vanishes, and the highs merge into one center.

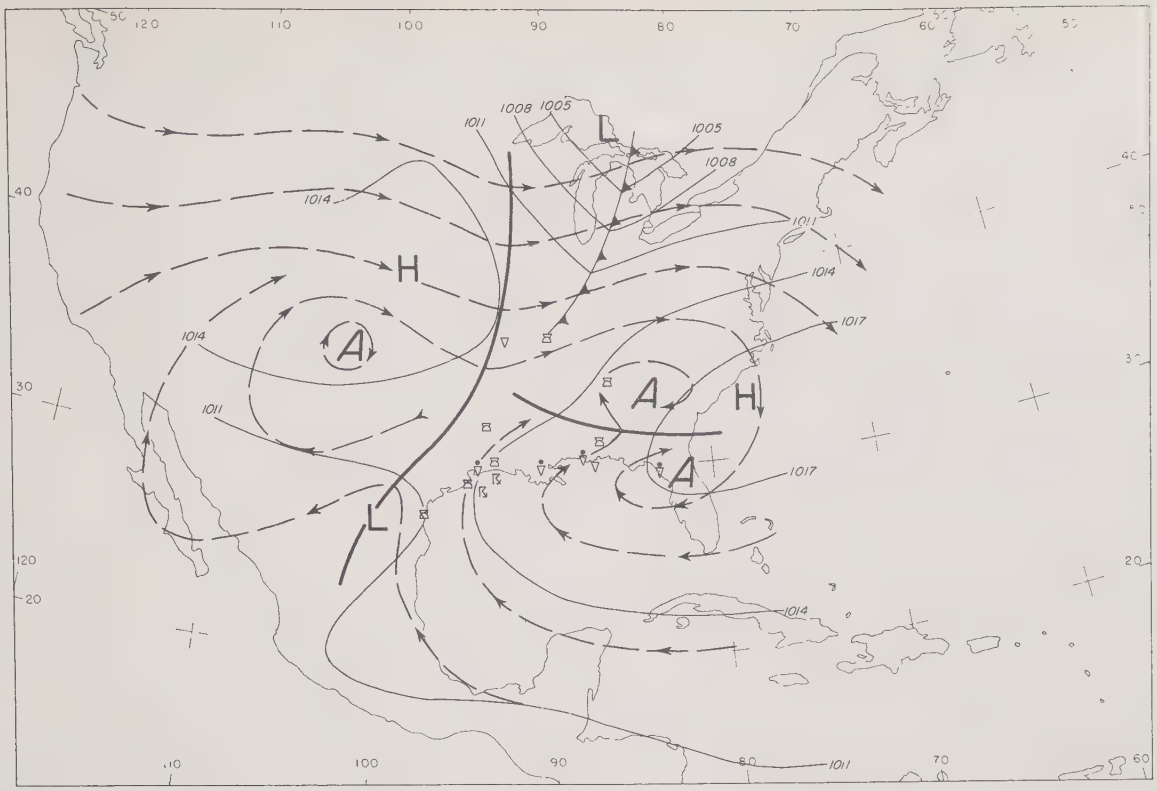

FIG. 4a.--Surface isobars, September 1, 1943, 1330 EST, and streamlines at 10,000 feet.

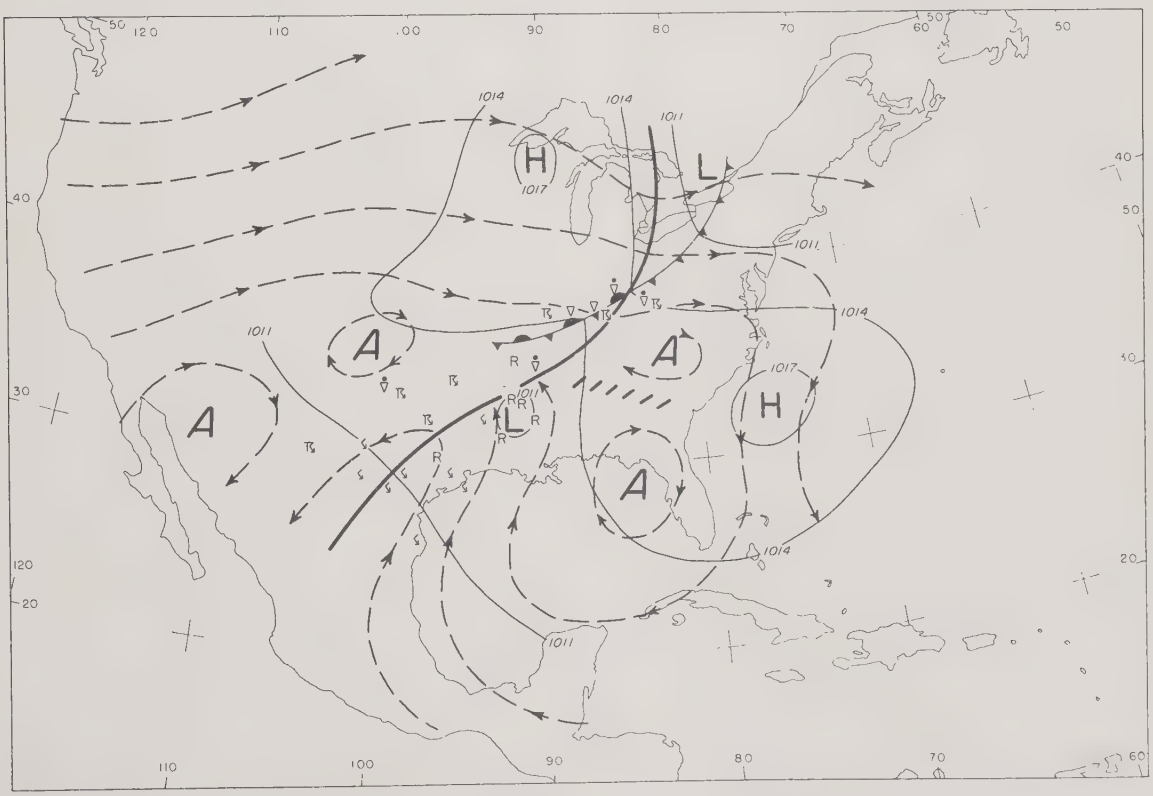

FIG. 4b.--Surface isobars, September 2, 1943, 0130 EST, and streamlines at 10,000 feet.

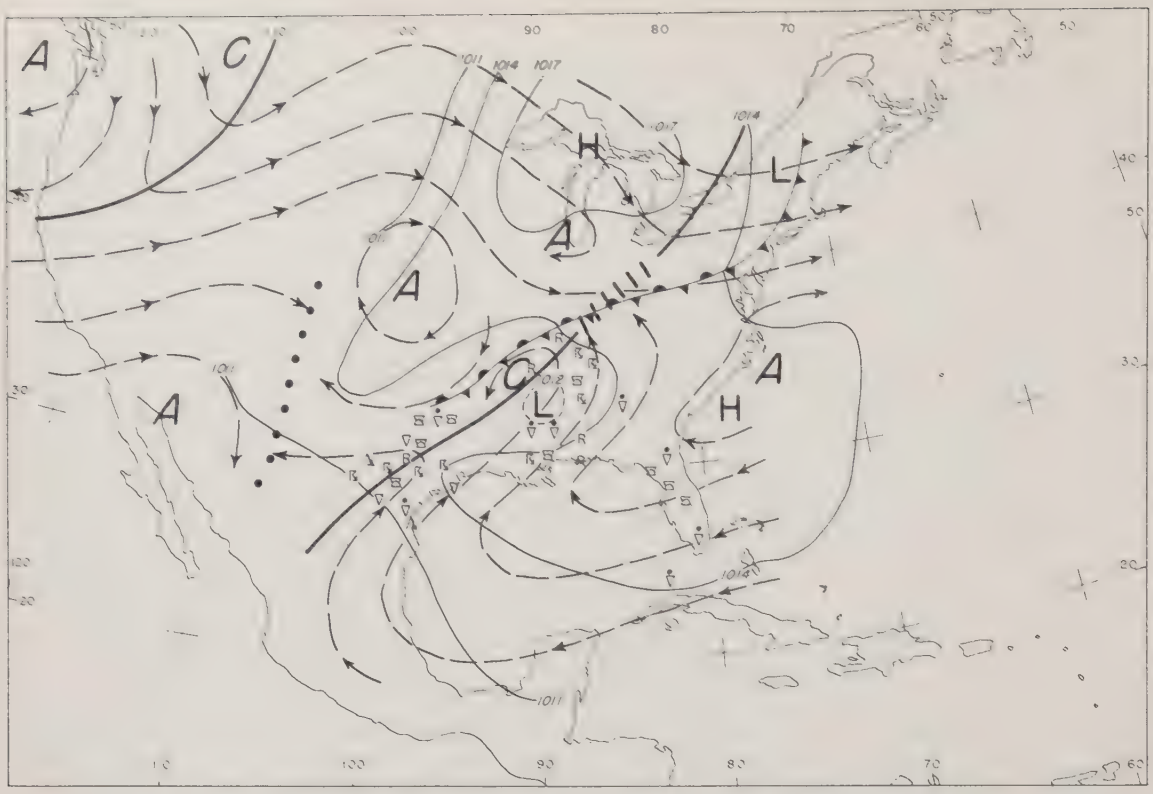

FIG. 5.--Surface isobars, September 2, 1943, 1330 EST, and streamlines at 10,000 feet.

The transition from a polar to a tropical pattern can rarely be deduced from changes in the configuration of the surface isobars. Occasionally, odd-looking lows emerge even in the surface pressure field that cannot be explained or forecast by the conventional methods. For example, several small cyclonic vortices attended by heavy rains and thunderstorms developed in eastern Texas and Louisiana during the first days of September, 1943 (Figs. 4-5). These centers gradually drifted northeastward. Prior to their development a westerly pattern predominated over the United States (Fig. 4a). Northerly winds aloft that developed along a large portion of the Atlantic Coast, plus the fact that no new disturbance in the westerlies arrived on September 1, served as a clue that stagnation and the development of upper easterlies would soon begin south of Latitude 40°. In addition, the surface and upper highs in the southeast were located at the same latitude.

The southern portion of the polar trough in the central United States moved but little during the afternoon of September 1 and during September 2. Continued eastward displacement north of Latitude 40° caused the entire trough to rotate clockwise and eventually (Fig. 5) led to a disintegration of those

portions of the trough no longer normal to the upper current.

Although the upper anticyclone centered near Amarillo on September 1 had advanced northeastward to Kansas on September 2, the outstanding occurrence was the separate anticyclonic development in the Chicago area. The sequence portrayed above is typical of a large number of summertime cases: the westerly winds initially weaken; 6-12 hours later a few light northerly and northeasterly winds appear on the winds-aloft chart, though a complete anticyclonic eddy is not yet in evidence. Another 12 hours later one can draw a closed streamline.

Great strengthening of the cyclonic shear along the southern part of the polar trough had taken place between September 1 and 2, and, since the streamlines south of the trough changed but little with time, it is clear that there had to be strong convergence in the current that arrived from the Gulf. The closed low which formed north of Lake Charles during the afternoon of September 1 was located entirely in the tropical air, whereas the polar front had definitely stagnated much farther north. Drifting northeastward with the mid-tropospheric current the center rapidly extended itself into the upper air on September 2, as it approached the Memphis area, where the upper trough lay close to the frontal zone.

Premature arrival of a strong system in the northwest during the afternoon of September 2 hinted that the high over northern Illinois would not have a chance to establish itself firmly. The sequence that was initiated toward the establishment of tropical conditions in the United States could not be completed, and the westerly pattern took hold again.

IV. GENERAL COMMENTS ON SUBTROPICAL FORECASTING

It is not possible, at least at present, to devise simple models of the subtropical disturbances and the mass convergence and divergence connected with them. The assumption of broad, nonshearing zonal currents, so useful in the central parts of the polar westerlies and tropical easterlies, must be discarded. Since shear is the principal destabilizing process known in large-scale atmospheric motion, steady state solutions for moving subtropical disturbances should not be expected. In practice, one will rarely find a moving system that does not undergo marked changes between two maps 6 hours apart. As there is no unique relationship between the large-scale map patterns and the appearance of organized convection, other factors which have a bearing on thunderstorm formation and forecasting will be discussed briefly.

1. The Temperature Lapse Rate

As is well known, thunderstorms cannot form in air masses with large subsidence inversions in the lower layers. The temperature lapse rate must exceed the moist adiabatic. Increasing steepness of the lapse rate beyond the moist adiabatic, however, except for the layer near the ground, was not indicative of higher probability of thunderstorm formation. The atmosphere pays the price of increased stability for replenishment of its moisture. Air with a nearly dry-adiabatic lapse rate is likely to be very dry. Conversely, superior air has the steepest lapse rates. Thus, if other conditions are favorable, the fact that the lapse rate exceeds the moist adiabatic only slightly should not be considered as an obstacle to thunderstorm formation.

2. The Moisture Content

According to Byers (1), a moist layer of 10,000-foot thickness suffices for thunderstorm occurrence. This estimate certainly holds true along the Gulf Coast. In fact, thunderstorms developed on numerous occasions in weak situations, when the relative humidity of the air columns involved was less than 50 per cent between 5,000 and 10,000 feet at the preceding midnight observation. The air that arrives from the Gulf is always very moist in the lowest levels, and the southerly flow near the ground is very persistent. A dry upper current that moves eastward along the coast in a nondivergent field of motion will increase its moisture content due to vertical mixing. The upper moistening may proceed so rapidly that clouds develop in the originally dry upper current even on the first afternoon of its appearance along the coast. The local

addition of moisture through evaporation from the ground is also of major importance, especially after periods of considerable rainfall, and should by no means be discounted. Every careful observer of local conditions and airways sequences will note that, on the first day following extensive rainfall, afternoon cloudiness tends to be very heavy in spite of establishment of anticyclonic control and that scattered afternoon thunderstorms frequently develop.

3. Pressure Changes

Surface 24-hour pressure falls frequently coincided with convection areas and at other times did not. The same applies for 24-hour surface pressure rises. Regions of upper pressure fall, however--usually in connection with cooling aloft--coincided more closely with thunderstorm activity. The correlation probably would have been even better if 12-hour pressure changes corrected for the diurnal effect had been available. It is definitely worthwhile to draw isolines of the 24-hour pressure and temperature change on upper charts, such as the 10,000-foot and the 15,000-foot charts, and to keep track of the path and intensity changes of the change centers, provided always that the changes are sufficiently large and the data are accurate enough to be believed.

4. Thermal Advection

The effect of advection, notably differential advection at different altitudes, may be considerable in the subtropics except in the layer near the ground. There the steady flow from the Gulf is interrupted only occasionally due to frontal passages. Therefore, cold-air advection above 3,000-5,000 feet will in general cause the lapse rate to steepen and warm-air advection will increase the stability. The same is not necessarily true in the higher latitudes, where the advection near the ground may have the same sign as the advection aloft and may even exceed it.

The arrival of superior air from the Gulf, coincident with the appearance or production of large temperature inversions, most frequently between 3,000 and 10,000 feet, is of major importance. The weather will become fine, even though the synoptic situation may be favorable for thunderstorm activity. If the stable air columns enter an active system, the convection will die out at least until convergence operating on these columns has removed the inversion. This is ordinarily possible, since the wet-bulb potential temperature generally decreases through the inversion. The convective stability of the air and the amount of stretching necessary before convection can resume is readily obtained from an energy diagram.

5. The Instantaneous Vorticity

In spite of the great influence of the change of vorticity for the formation of organized convection, little correlation exists between thunderstorm occurrence and instantaneous large-scale cyclonic vorticity. It is an outstanding characteristic of the Gulf Coast that a very large number of thunderstorms occur when the flow is anticyclonically curved in the lower and middle troposphere and when, in addition, the shear is anticyclonic. Thus the instantaneous flow curvature, regarded so highly by some middle-latitude meteorologists, fails completely as an indicator of areas of cloudiness and precipitation in the subtropics. It is therefore suggested that the cyclonic curvature itself probably is not mainly responsible for its habitual coincidence with bad-weather areas in higher latitudes but that other dynamic and thermodynamic factors, of greater importance for the formation of rain, have a high positive correlation with cyclonic curvature in the middle latitudes, whereas in the subtropics such a correlation does not exist.

6. Changes of Vorticity

As stressed previously in this report, a change of the relative vorticity of an air column cannot be assumed to express itself mainly in a change of curvature in the subtropics but may also appear as a change of the wind shear. As yet, no general rules are known which denote just how a change of vorticity will manifest itself. A statement useful for forecasting purposes, therefore, can be made only in certain prescribed fields of motion.

For instance, there is a marked tendency for the polar trough to persist in its mean position (Table 7). Streamlines and trajectories will coincide approximately in that case, and it is possible to examine the weather distribution to be expected along the subtropical portion of the trough (Fig. 6) with a qualitative application of the vorticity equation. It is assumed that the trough does not slope with elevation and that the streamlines represent the flow of a layer 10,000 feet thick, based on the 3,000-foot level.

The points A, B, and C are chosen so that the relative vorticity is approximately zero in their vicinity. Let the air columns initially located at A, B, and C travel to A', B', and C', without altering the general pressure and wind distribution--a common occurrence. Along the trajectory B-B' the flow curvature becomes more anticyclonic and the shear more cyclonic. If a column had neither stretched nor shrunk during the passage from B to B', the cyclonic shear at B' must be about 7 mps per 250 km, using reasonable values for the change of curvature. Cyclonic shears considerably in excess of the indicated value frequently persist in a narrow band just west of stationary polar troughs in the subtropics indicating convergence. Since the air columns

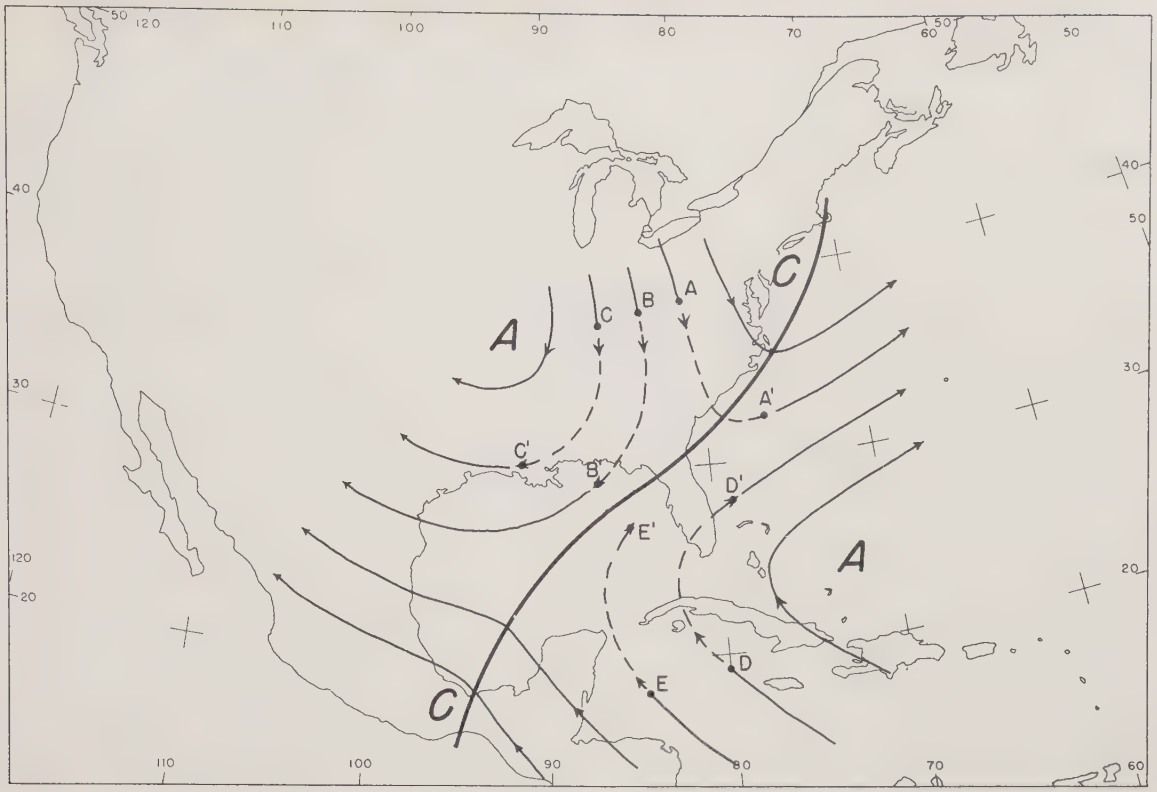

FIG. 6.--Trajectories of the air columns initially located at points A to E during stagnant conditions when the broad scale polar trough lies near its average position.

which move along a path such as B-B' usually remain in the convergent zone for considerable time, thunderstorm activity commonly results even though the air may start southward from B with a low initial moisture content. After establishment of the stationary pattern, thunderstorms first break out in western Florida when sufficient time has elapsed to permit columns to complete the trajectory B-B' and to accumulate moisture. The thunderstorms then spread westward along the coast line.

Although the columns moving on the trajectory C-C' gain anticyclonic flow curvature similar to the air on B-B', they do not acquire cyclonic shear but some anticyclonic shear. Thus they must shrink vertically. Very fine weather should prevail in the region of the trajectory C-C', and an observer going from B' to C' should experience a rapid transition from cloudy to extremely clear skies. This is indeed often the case. Disturbed weather will prevail along the coast from New Orleans to Jacksonville and extend about 100 miles inland, depending on the situation. A little farther north the sky is cloudless.

Although the trajectories A-A' and B-B' diverge sharply, there is no

need for net divergence to occur in the compartment AA'BB', since the wind speed may decrease sufficiently toward the polar trough to compensate for the directional divergence. Columns moving from A to A' need not shrink as they pass across the polar trough if the counterclockwise turning is adequate to offset the increasing anticyclonic shear encountered near the subtropical col. Weather near the col thus will be determined largely by the shape of the col itself. In Figure 6 the northern trough is drawn narrow with the highs elongated, and the weather is likely to be active. However, if the lows are elongated and the highs narrow, fair skies should predominate according to vorticity considerations. The latter type of col corresponds to Figures 113G-113I, in S. Petterssen's textbook, Weather Analysis and Forecasting (5), which illustrate a col with anticyclonic rotation superimposed on a linear field of motion. The former type is similar to that shown in Figures 113D-113F.

The region east of the polar trough is far better suited for the maintenance of widespread convective zones than the area to its west. The two broad currents on either side of the polar trough have a maximum rate of anticyclonic turning in the subtropics. This turning can be accomplished west of the trough in the absence of shrinking only through the development of a rather large cyclonic shear. East of the troughline, however, the air columns initially located at D and E tend to turn anticyclonically because they move toward higher latitudes. A small decrease of the rate of clockwise turning and displacement of the air toward increasing cyclonic or decreasing anticyclonic shear will readily necessitate stretching followed by convection. This is particularly pronounced on the trajectory E-E'. The trajectory D-D' encounters the greatest cyclonic shear over Florida, a situation duplicated on many days during summer. The predominant flow pattern augments the tendency for convection over the peninsula due to heating and can thus account for the high thunderstorm frequency over Florida during summer.

Convergence along D-D' will be greatest, if the Bermuda High has a large meridional extent. If, however, the polar westerlies are strong and the streamline amplitude is small, then the air columns which penetrate into the middle latitudes from the tropics will often recurve very sharply and the anticyclonic turning will greatly exceed that prescribed by the constant vorticity trajectory without divergence or convergence. Clear skies should predominate then at both ends of the subtropical high, which would be elongated E-W. Air-mass thunderstorms, however, are still possible in the central parts of the high, where little air motion takes place.

One important exception to the principles just discussed should be noted.

In certain southwesterly currents in the middle troposphere, a band of particularly strong winds occasionally appears in the central portion of the current. General cloudiness and thunderstorms may develop there and spread into the shearing zones on both sides, without preference for the cyclonic side. The same occurs within the easterly currents.

7. Moving Waves in Relation to Standing Waves

Several meteorologists have commented on the fact that the superposition of two wave troughs will increase their amplitude. In particular, Fultz (2) noted that the NW troughs become more pronounced as they approach a large-scale trough with the northwesterly current to its rear, while they weaken rapidly after passing it. Waves in the easterlies that move toward the low latitude portion of a large-scale trough produce an increase of the amplitude of the latter with great regularity. The subtropical col, often very indistinct prior to the arrival of the wave, becomes well defined, and the bad-weather zone attending the polar trough intensifies.

As long as the succession of NW troughs continues, a stationary polar trough will remain oriented similar to Figure 6. A change in the broad scale situation, primarily a flattening of the streamlines to a more E-W orientation, causes the NW trough movement to end, and an eastward displacement of the northern part of the polar trough begins. A westward movement of the low-latitude part starts simultaneously. All the systems connected with the subtropical col then rotate clockwise about the col, which may remain stationary and serve as the center of rotation. If the zonal flow continues to predominate the high- and low-latitude portions of the polar trough will finally split, the high-latitude portion moving eastward and the low-latitude portion westward. If, however, the NW trough motion resumes quickly, the subtropical col will not break down but will maintain itself, and the subtropical highs will assume a more meridional arrangement.

V. SPECIFIC BEHAVIOR OF FLOW PATTERNS

1. Polar Trough near East Coast

If a well-marked polar trough remains stationary near its mean seasonal position, heat and drought prevail in the South, west of the Mississippi. Although nearly a quarter of all the days studied fell within the classification now discussed, the percentage of thunderstorms is very small in eastern Texas and increases but gradually from there eastward and southward. At Fort Worth the relative thunderstorm frequency was only 5 per cent, while the percentage increased to 35 at New Orleans and became still higher farther east. All stations experienced a large percentage of their dry days during the predominance of the pattern presently discussed (Table 8).

Special situations.--(a) If the upper troughline over the Gulf lies fairly close to the Alabama and Louisiana coasts and persists there, the coastal stations from Apalachicola to New Orleans and sometimes even Lake Charles are located in that zone northwest of the polar trough that may have a strong cyclonic shear (cf. Fig. 6). Thunderstorms along the eastern part of the Gulf edge are quite common, and there are numerous reports of lightning to the south at night.

If the principal trough is situated just off the Atlantic coast, the influence of NW troughs that move southeastward in the eastern United States will extend to the Mississippi Basin. A considerable percentage of the Vicksburg thunderstorms and a smaller portion of the New Orleans thunderstorms are due to the arrival of such moving perturbations, which usually can be

TABLE 8

FREQUENCY OF WEATHER TYPES WITH POLAR TROUGH NEAR EAST COAST

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days	5	5	2	9	14	14
Per cent of all days without precipitation	36	42	33	33	41	29
Per cent of days in pattern with thunderstorms	10	10	5	15	35	20
Per cent of days in pattern with no precipitation	80	80	95	80	65	75

traced without much difficulty on the upper-wind maps between 10,000 and 15,000 feet.

b) Attempts to break down the stationary pattern commonly originate in the west, although a favorable situation must prevail simultaneously in the Atlantic if the attempt is to be successful. If the East Coast trough holds, waves in the westerlies that arrive from the Pacific will be carried northeastward with the general southwesterly current over the Rockies, and they will at best affect northern Texas and northern Louisiana. Under such circumstances a good trade-wind inversion usually exists in the current drawn northward from the Gulf. Thunderstorms, therefore, are rare in southern Texas, but their frequency increases very rapidly north of Fort Worth.

c) It is quite common for a certain amount of clockwise rotation of the subtropical col to take place, causing the polar trough to orient itself even more NE-SW than is ordinarily the case. The smaller troughs along the East Coast then proceed almost due southward, and their axis is oriented almost E-W. Except for the layer near the ground, the moisture necessary for thunderstorm formation in connection with these troughs does not come from the Gulf but instead moves gulfward from the Great Lakes region. The situation corresponds closely to that described by Namias (3). In several instances the moist layer proceeded on a clockwise path and reached Texas from the northeast or east, analogous to Namias' description.

Because of the predominant northerly flow along the East Coast, southward motion of cold fronts oriented E-W can occur during the situation just described. Usually these fronts are indistinct west of the Appalachians, but occasionally polar air will spread toward Vicksburg and New Orleans along a line that is oriented NW-SE and advances southwestward. Vicksburg recorded lightning to the northeast a few times during the approach of such a system, but for the most part only stratocumulus, broken to overcast, resulted there and at New Orleans.

Ordinarily, the polar air is greatly modified when it reaches the Tennessee Basin and tends to stagnate there. A shallow surface trough that contains more than the average convection then extends westward from the Carolinas. Such a weak, stationary trough comes to life each time an upper trough passes over it from the north, and thunderstorm activity spreads. The upper trough usually can be picked up in the New England or in the Eastern Lakes area, depending on the situation. A particularly strong perturbation aloft may cause displacement of the surface trough to the Piedmont plains or even to the vicinity of the Gulf Coast. In this connection it may be mentioned not only that the arrival of a wave in the westerlies strengthens the portion of the polar trough

north of the subtropical col but that an intensification takes place even along the tropical parts of the trough in response to the deepening farther north. Numerous thunderstorms in the South, not easy to understand otherwise, can be forecast by watching the perturbation north of Latitude 35°.

Termination --The polar trough usually rotates clockwise with time and eventually breaks up due to the action of Pacific disturbances. The streamline amplitude in the north decreases both over the United States and the Atlantic Ocean. Then, as the northern part of the polar trough moves into the central Atlantic, its tropical extension starts westward as a wave in the easterlies.

On four occasions during the three summers analyzed the clockwise rotation of the trough had proceeded so far that its tropical section was lying nearly east-west (cf. Table 7). Northward motion as a shearline rather than transverse wave motion followed. Three times the strength of the westerly current that developed eastward from the Rocky Mountain area was so great and the latitude to which it extended sufficiently low as to obliterate entirely the low-latitude section of the polar trough and to bring the whole United States under the influence of the westerlies. An apparent retrogression of the polar trough occurred four times. On these occasions a fresh polar air mass reached the United States, causing deepening aloft and westward transfer of the greatest streamline amplitude to the Mississippi Basin.

2. Polar Trough near Mississippi Basin

The picture presented in Table 9 is less clear cut than that of Table 8. In eastern Texas the percentage of thunderstorm days is far greater and the frequency of dry days less. The coastal stations have the highest relative thunderstorm frequency. The three inland stations often are in polar air, while the boundary between tropical and polar air is just north of the coastline. Although this boundary itself is likely to be active, the rather dry and stable air to its north tends to be a poor thunderstorm producer as is to be expected.

Special situations.--A wide variety of sequences took place, and only several outstanding cases can be discussed here.

a) When a smaller perturbation in the westerly or northwesterly current to the rear of the large-scale polar trough merges with the latter, the entire system tends to advance eastward. This eastward motion stops after 6-12 hours and then the large-scale trough will return to its former position. Since there must be a considerable amount of net mass convergence east of the trough to accomplish this retrogression, thunderstorm activity during the periods of westward motion can be severe, particularly south of the polar front. All

TABLE 9

FREQUENCY OF WEATHER TYPES WITH POLAR TROUGH
NEAR MISSISSIPPI BASIN

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days	12	12	9	9	11	8
Per cent of all days without precipitation	7	6	7	9	8	9
Per cent of days in pattern with thunderstorms	55	65	35	30	70	30
Per cent of days in pattern with no precipitation	40	25	50	60	30	60

stations experienced prolonged thunderstorms of moderate to severe character under these circumstances.

In general, only cirrus and altostratus overcasts overlie the polar air just west of the main upper trough, while the polar air is actively moving toward the lower latitudes. As soon as its southward progress has stopped, however, the influence of smaller upper perturbations tends to make itself felt with a resumption of shower and thundershower activity in contrast to many wintertime situations. The passing perturbations are NW troughs and are of the same type as those that move down the East Coast when the polar trough is located in the western Atlantic. Consequently, the same considerations apply. The passing zones of convergence and divergence, associated with large increases and decreases of the moisture content aloft, can be traced quite regularly, and one should by no means think that areas located under the northwesterly current aloft will have good weather. While many days will be fair, others will have considerable thunderstorm activity. This activity can be anticipated by noting the perturbations that move down from the northwest and the moisture content and stability of the air through which they pass.

b) Difficult situations arise when the large-scale trough rotates counterclockwise. This rotation is initiated by the appearance of a dynamic high over New England, eastern Canada, or even the Great Lakes area. Attempts to form such a high can be noted on the winds-aloft map during any summertime situation when the activity in the belt of westerlies decreases. Ordinarily, the westerly flow resumes too quickly, and the high has no chance to consolidate. Whenever it becomes firmly established, however, it acts as a powerful brake on the general circulation and greatly influences even the subtropical weather. The normal anticyclonic shear in the middle latitudes

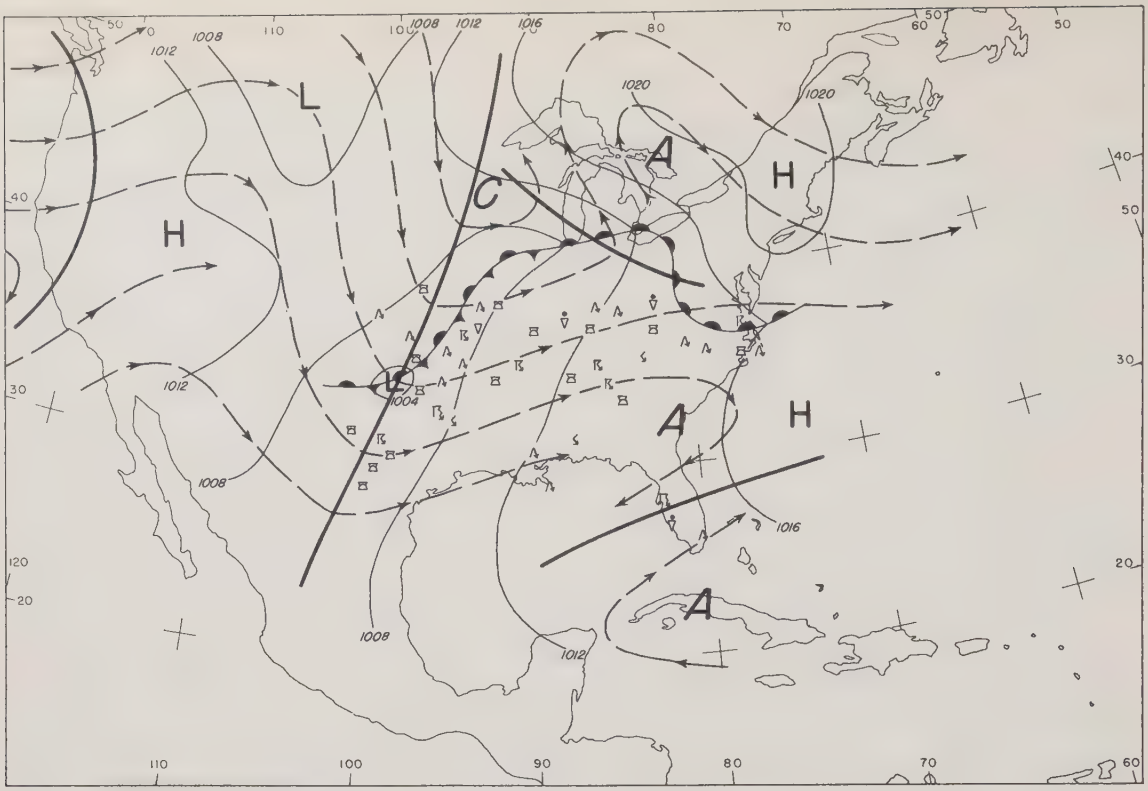

FIG. 7a.--Surface isobars, August 27, 1940, 1930 EST, and streamlines at 10,000 feet.

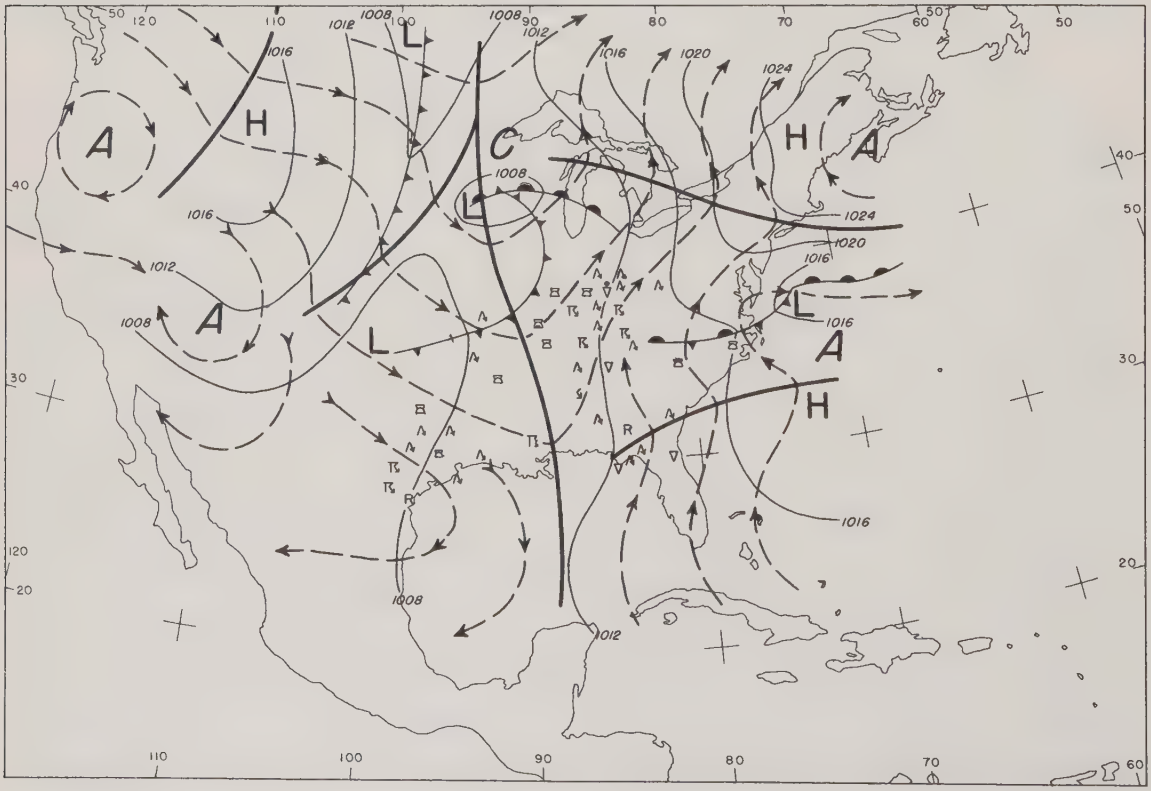

FIG. 7b.--Surface isobars, August 28, 1940, 1930 EST, and streamlines at 10,000 feet.

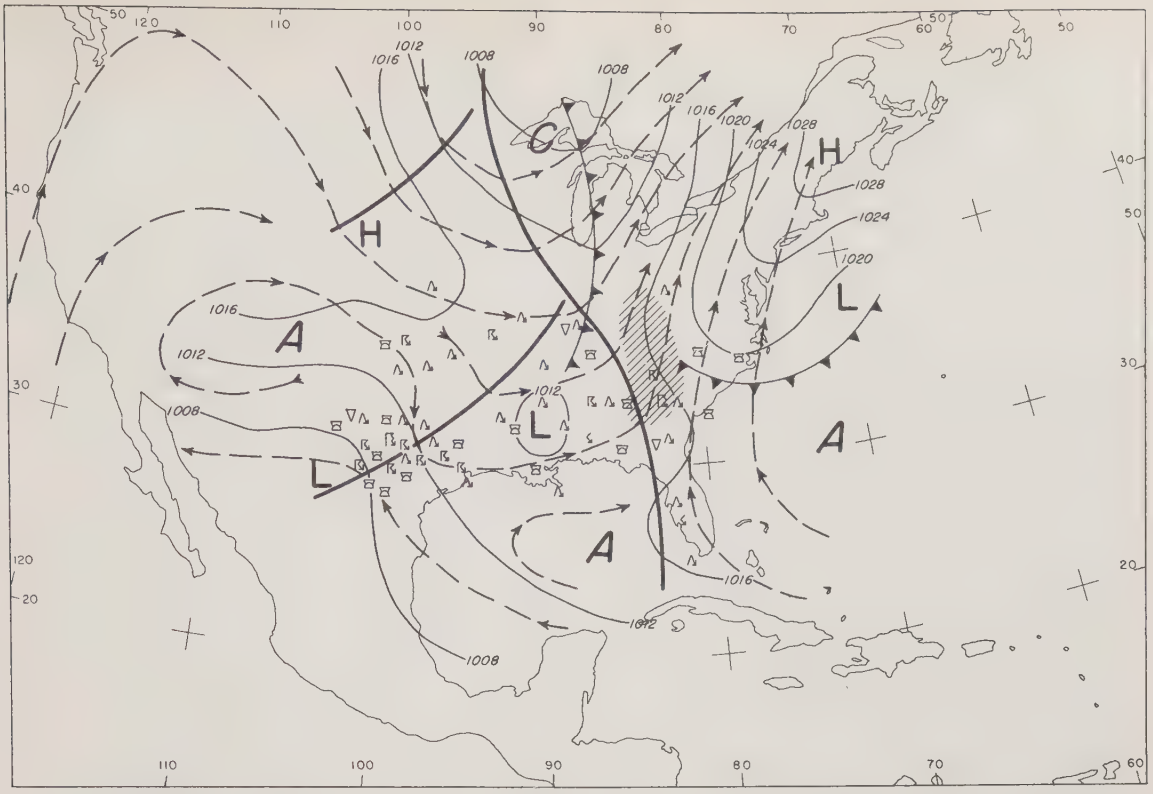

FIG. 7c.--Surface isobars, August 29, 1940, 1930 EST, and streamlines at 10,000 feet. Heavy precipitation occurs in shaded area.

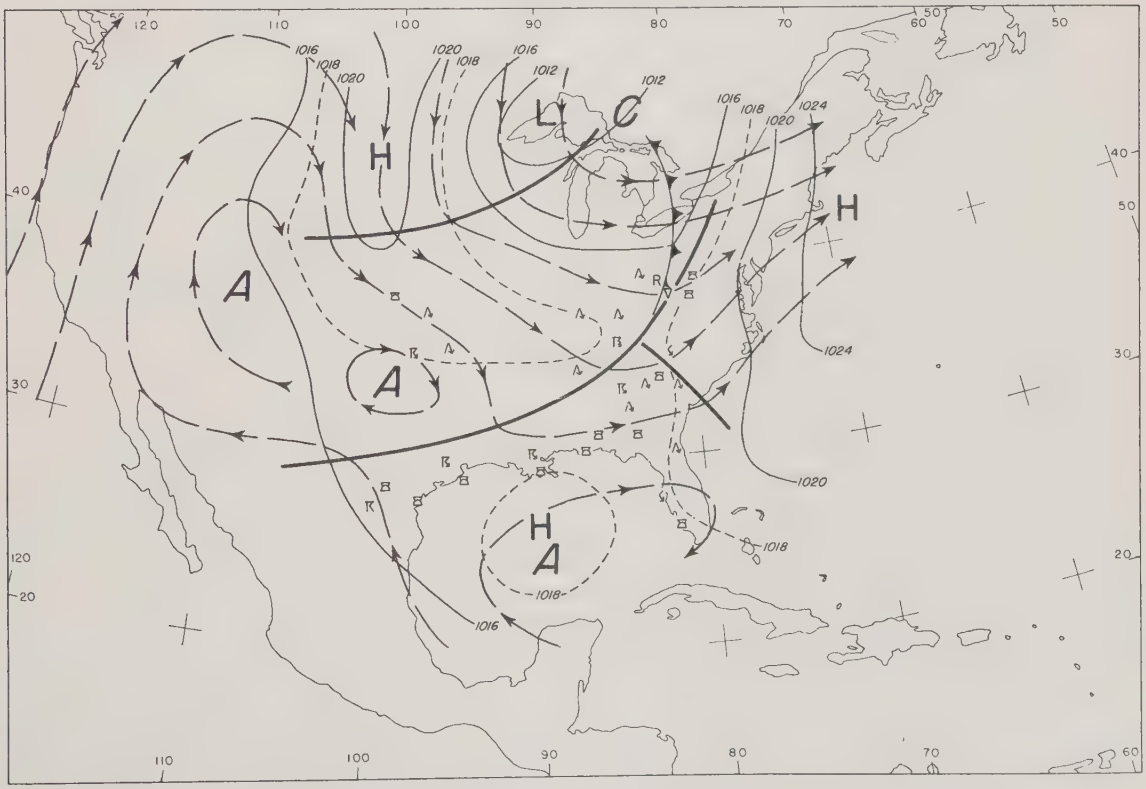

FIG. 7d.--Surface isobars, August 30, 1940, 1930 EST, and streamlines at 10,000 feet.

then is replaced by a cyclonic shear (cf. Figs. 7a, b). The region of anticyclonic shear either vanishes entirely or is displaced south of its normal position. Eastward motion of troughs ceases in the northern United States and southern Canada but may continue in the south. A gradual change of the orientation of the large-scale trough to NW-SE results.

The northeastern high does not maintain itself throughout the series reproduced in this report (Figs. 7a-d) but is eventually forced out to sea. In other instances (cf. July 7-11, 1943) the high did remain stationary for a number of days, and closed upper lows formed in an E-W shear zone aloft analogous to the one extending from New York to Lake Michigan on Figure 7b.

Weather maps with counterclockwise rotation of the polar trough, and occasionally even southeasterly isobars at the surface over a large portion of the United States, are well known as heavy rain producers. The lack of anticyclonic turning of the air columns that move up from the south with increasing latitude probably accounts for this. The weather reports at 7:30 P.M., August 27, 1940, already indicated the presence of a moist unstable air mass in the central and southern United States. On the 28th and 29th, as the counterclockwise rotation progressed, rainfall in the southeast became heavy. The organized convection occurred mainly ahead of the rotating polar trough. However, as indicated on Figure 7b, there was also some activity to its rear, at least south of the cold front.

The presence of an E-W shearline, analogous to Figure 3, contributed to the intensification of the rainfall. This shearline moved northward on August 27 and 28 coincident with the counterclockwise rotation of the broad scale pattern, a decrease of the westerlies in the southern United States, and a large increase in the southerly wind component on August 28. Concurrence of the arrival of the shearline and the polar trough near the Appalachians on August 29 resulted in heavy rainfall, which took place in the absence of any well-marked surface low. The upper-air analysis, offered in Figure 7, however, supplies a decisive clue.

On August 29 the shearline could not be located anymore on the map, probably due to the absence of wind observations in the heavy precipitation area. The breakdown of the polar trough on the 30th and the rearrangement of the wave pattern will be referred to in the following sections.

Termination.--Normally the polar trough might be expected to drift slowly to the East Coast and stagnate there. This happened in six out of the fifteen cases when a change occurred (cf. Table 7). The development of strong westerlies over the Rockies with very little meridional flow component twice caused the polar trough to lose its amplitude and disintegrate, the northern portion

advancing rapidly into the central Atlantic. On two occasions the arrival of a new polar air mass from the northwest produced a frontal pattern.

In three cases clockwise rotation with subsequent westward motion of the low-latitude portion of the trough took place. These situations were analogous to those described for the East Coast in the preceding section. Once a tropical disturbance came up from the Gulf during a period when a large-scale trough was stationary in the Mississippi Basin (September 15, 1943). Although this center did not attain hurricane intensity, it nevertheless became the determining factor for the Gulf Coast weather for several days.

3. Westerly Patterns

All stations received considerable contributions to their thunderstorm total while westerly patterns prevailed (Table 10). Outstanding are the high percentages at Fort Worth and Shreveport. These stations not only experienced many days with thunderstorms but also numerous days with severe thunderstorms.

Since smaller moving waves in the westerlies rapidly lose strength southward, the drop of thunderstorm frequency from Fort Worth to Galveston is not surprising. The subsidence zone over the Gulf associated with the westerly patterns, however, is usually less intense than during periods when a large-scale trough stagnates near the East Coast. Consequently, the air that moves northward from the Gulf is not so commonly marked by extreme dryness and stability. Rapid increase of the relative thunderstorm frequency between Galveston and Houston reflects the greater air-mass instability of the Gulf air, which, even after a short trajectory over land, may start to produce thunderstorms. The surprisingly high thunderstorm total at New Orleans also emphasizes this point.

Special situations.--(a) A fairly well pronounced quasi-stationary trough may overlie the Rockies and send smaller waves--SW troughs--ahead into Texas.

TABLE 10

FREQUENCY OF WEATHER TYPES WITH WESTERLY PATTERNS

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days	12	21	34	28	20	21
Per cent of all days without precipitation	27	24	14	19	24	24
Per cent of days in pattern with thunderstorms	20	45	50	40	50	40
Per cent of days in pattern with no precipitation	60	45	40	50	35	60

Southeasterly to southerly winds that turn slightly clockwise with height then prevail near the ground at the western Gulf Coast. The entire current turns anticyclonically with increasing latitude, and a pronounced anticyclonic shear is present. At the approach of a wave from the west a deep surface trough develops in the lee of the mountains. Strong convergence in this trough is responsible for the common appearance of severe thunderstorms in Oklahoma and northern Texas.

Organized convection zones accompany the moving perturbations, which are oriented nearly N-S when they begin the descent from the mountains. As they reach the eastern slope of the Rockies, their amplitude temporarily increases. At several stations, notably Big Springs, Texas (BZ), windshifts of nearly 180° may occur with the trough passage; and these windshifts are much greater than those reported farther north, where the waves are much more active. One deals with a topographic effect, and the large amplitude vanishes rapidly as the wave troughs pass Abilene on their way to Fort Worth, where the turning of the wind rarely is more than 45°. Often the only indication of a wave passage there is a strengthening of the southwest wind aloft.

The upper pressure and temperature variations connected with the disturbances can be traced from El Paso and Albuquerque to Oklahoma City and beyond. Even San Antonio pressures and temperatures regularly react to what happens farther north, although often the wind field does not change. Thus a plot of the upper 24-hour pressure and temperature change centers, especially at 10,000 and 15,000 feet, offers much help in forecasting the movement of the organized convection zones. Thunderstorms usually precede the wave troughs, and there are pressure falls aloft with cooling. To the rear, stations experience upper pressure rises, warming and drying. This weather distribution agrees well with that ordinarily observed in the vicinity of waves in the westerlies farther north.

Texas thus undergoes alternating days of dry and showery weather, although the air mass near the ground does not change at all and the low tropospheric flow from the Gulf remains undisturbed. An important variation occurs when an old wave in the easterlies arrives from the West Gulf area coinciding with the eastward motion of a wave in the westerlies from the mountains. The thunderstorm activity, even at Houston and Galveston, then becomes more intense. At Fort Worth a prolonged period of severe thunderstorms is likely.

Convection will also be more pronounced on the coast, if the entire sequence just described takes place about 5° latitude farther south than usually observed. The severe convection zone of Oklahoma and northern Texas then shifts to the coast: The air columns coming up from the Gulf still move in a field of anticyclonic shear. This shear, however, decreases with increasing latitude,

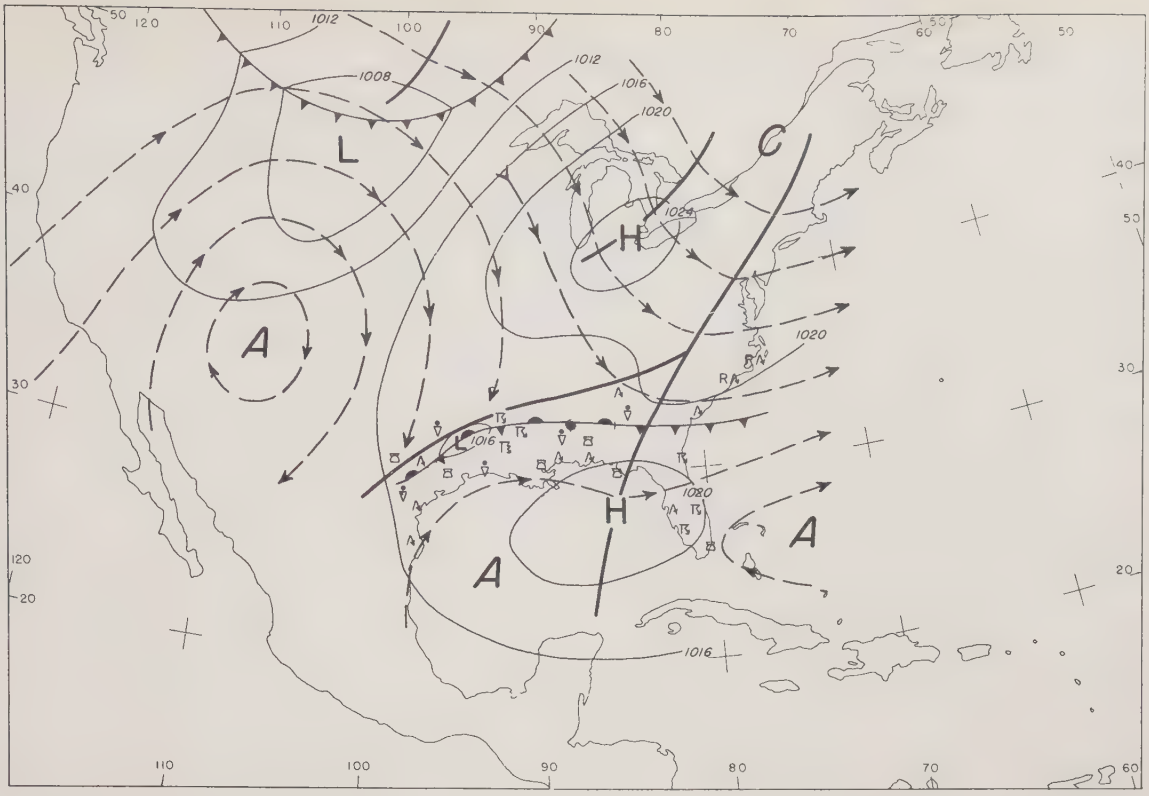

FIG. 8a.--Surface isobars, July 13, 1940, 1930 EST, and streamlines at 14,000 feet.

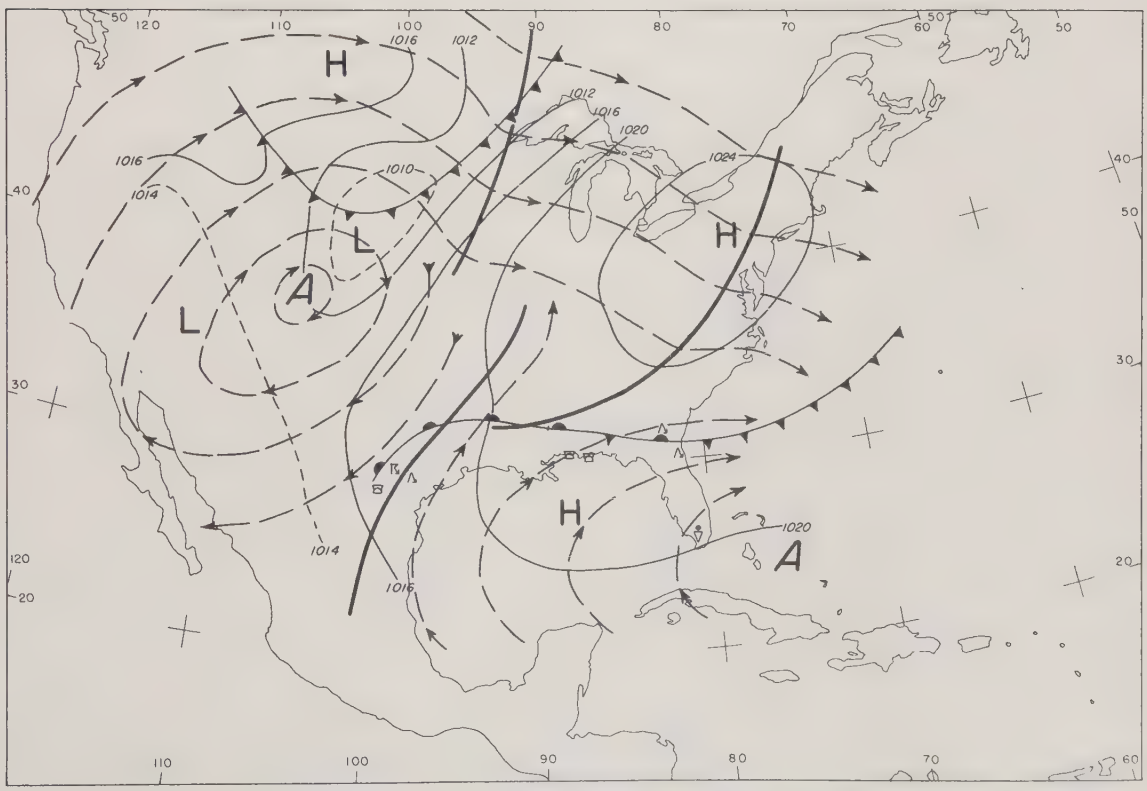

FIG. 8b.--Surface isobars, July 14, 1940, 0730 EST, and streamlines at 14,000 feet.

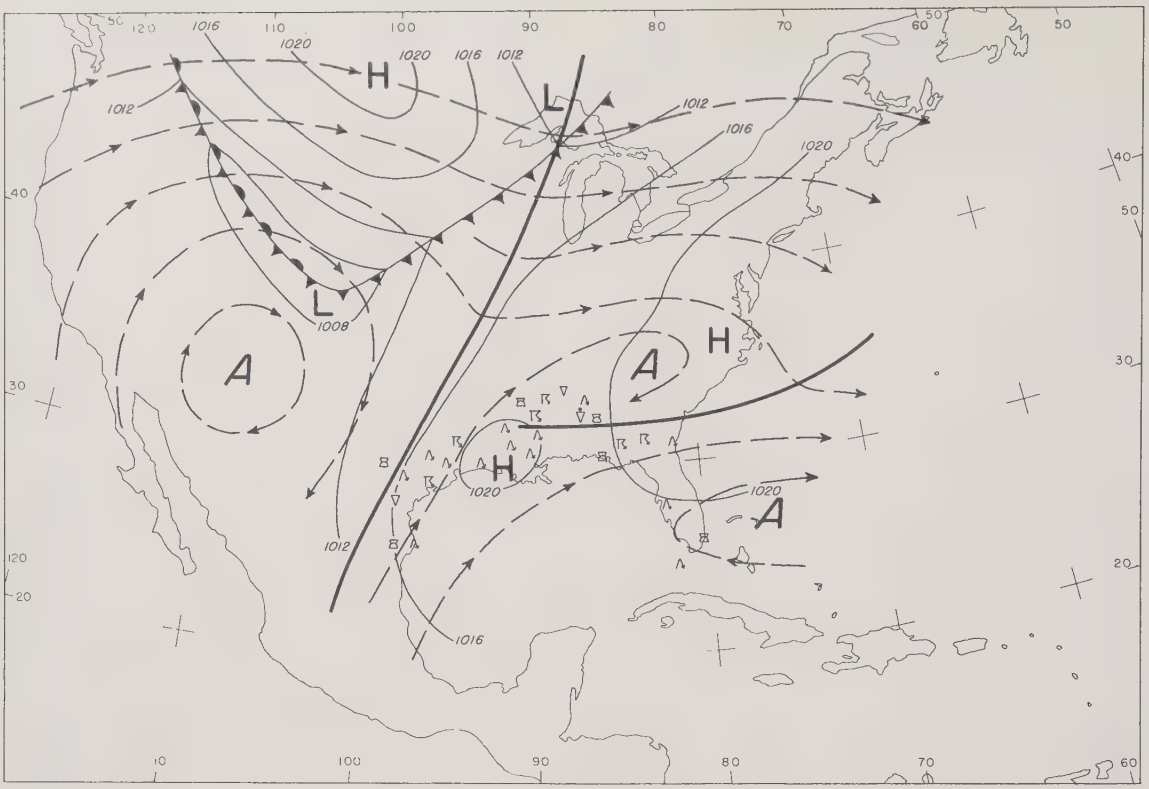

FIG. 8c.--Surface isobars, July 14, 1940, 1930 EST, and streamlines at 14,000 feet.

adding to the cyclonic vorticity in the southerly current.

b) A more complex and yet common situation arises when a large-scale trough that extends from the polar zone into the tropics crosses from the mountains into the Plains States. As stated previously by the author (6), the low-latitude portion of such a trough rarely is able to keep up with the polar part. Extraordinary convergence to its west would be required to produce eastward motion comparable to that in higher latitudes. Thus, a gradual clockwise rotation of the trough ordinarily takes place. The high-latitude part continues toward the East Coast, while in Texas the wave trough becomes nearly stationary (Figs. 9a, b). The central part of the troughline then is rotated into a NE-SW position; and while the portions in the far north and far south retain their orientation normal to the prevailing flow, the intermediate part that lies within the main anticyclonic shearing zone assumes an oblique orientation.

It appears to be a common property of atmospheric waves that they strive to maintain their transversal character. Any other orientation represents an unsteady state that is subject to quick adjustment. The portion of the trough-

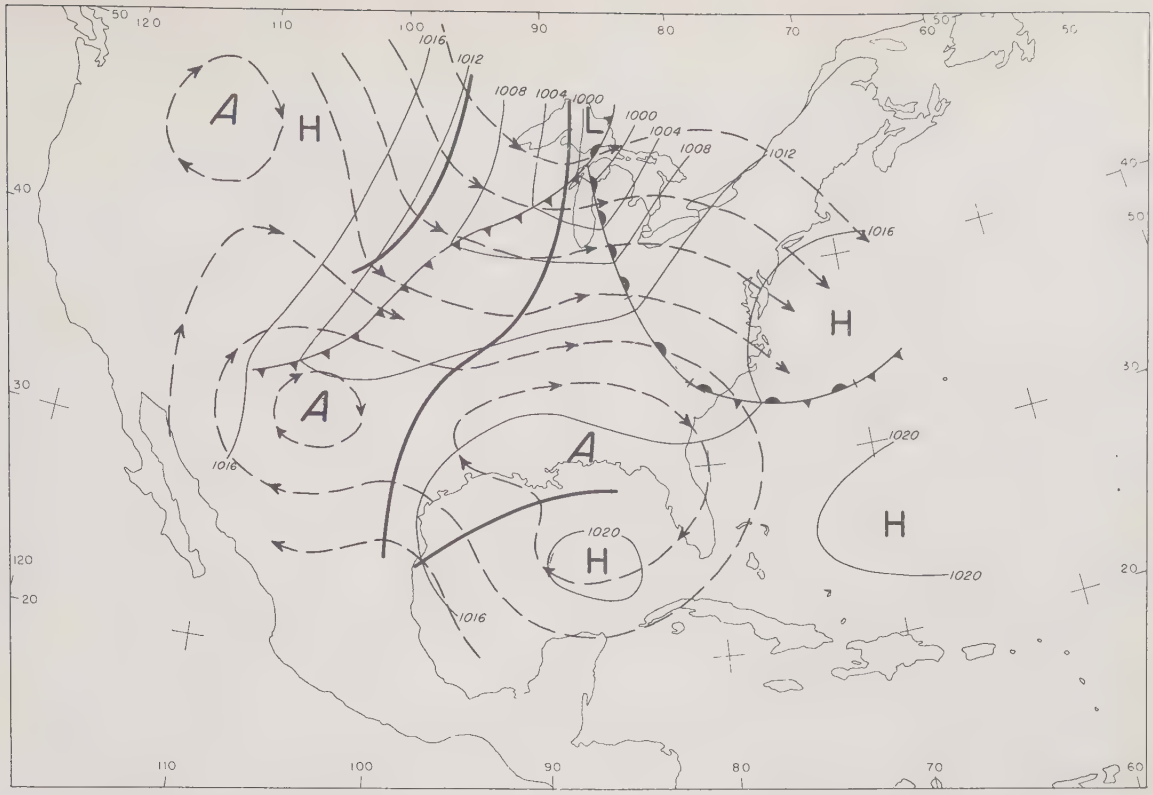

FIG. 9a.--Surface isobars, August 11, 1941, 1330 EST, and streamlines at 14,000 feet.

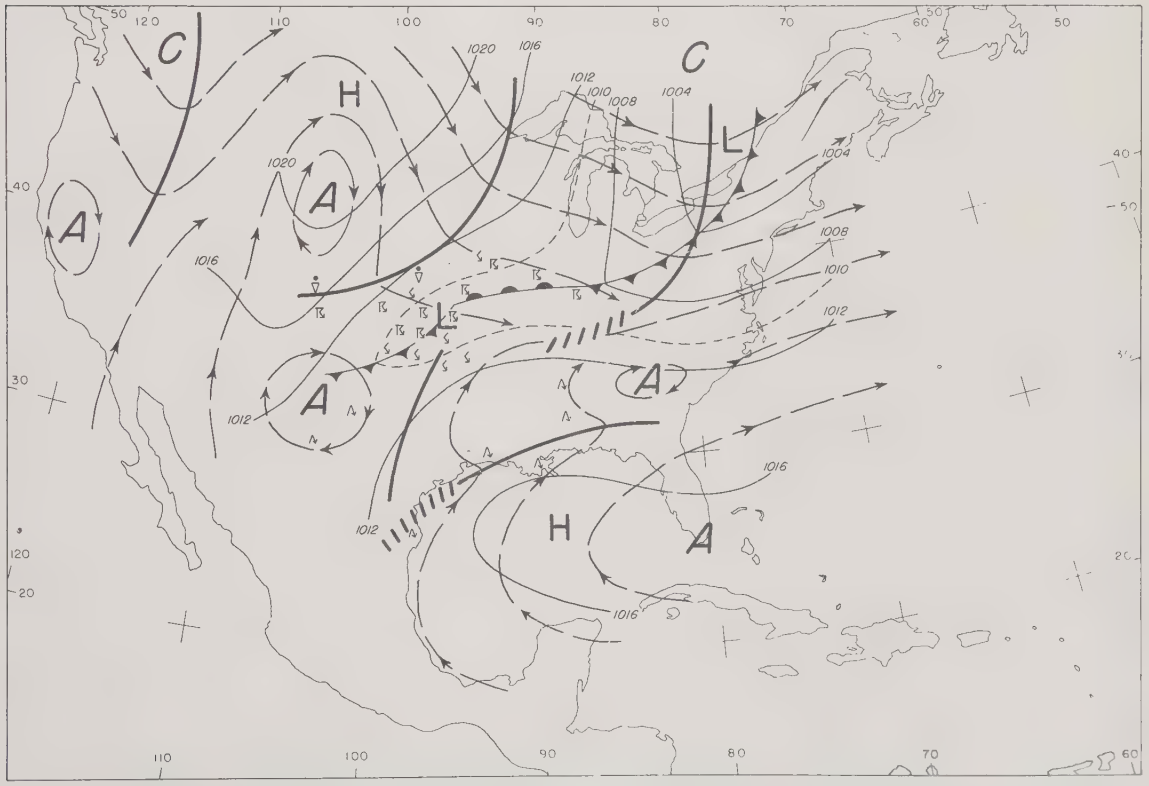

FIG. 9b.--Surface isobars, August 12, 1941, 0130 EST, and streamlines at 14,000 feet.

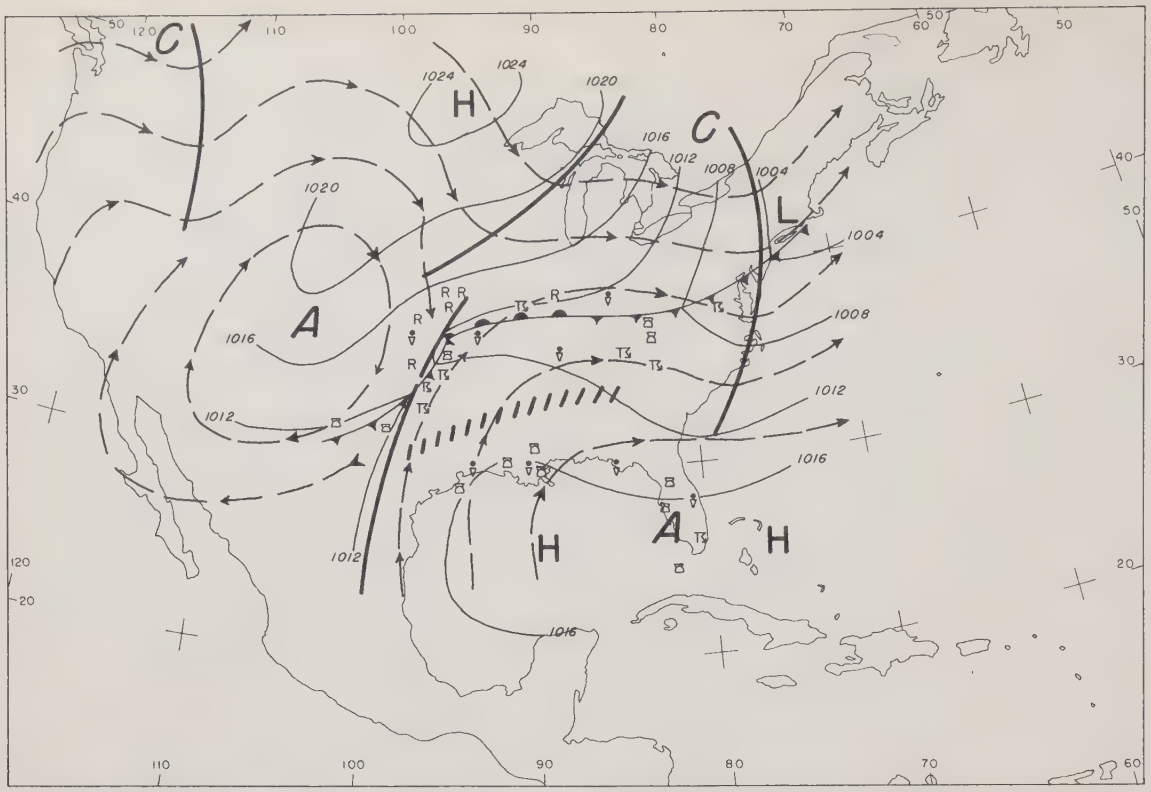

FIG. 9c.--Surface isobars, August 12, 1941, 1330 EST, and streamlines at 14,000 feet.

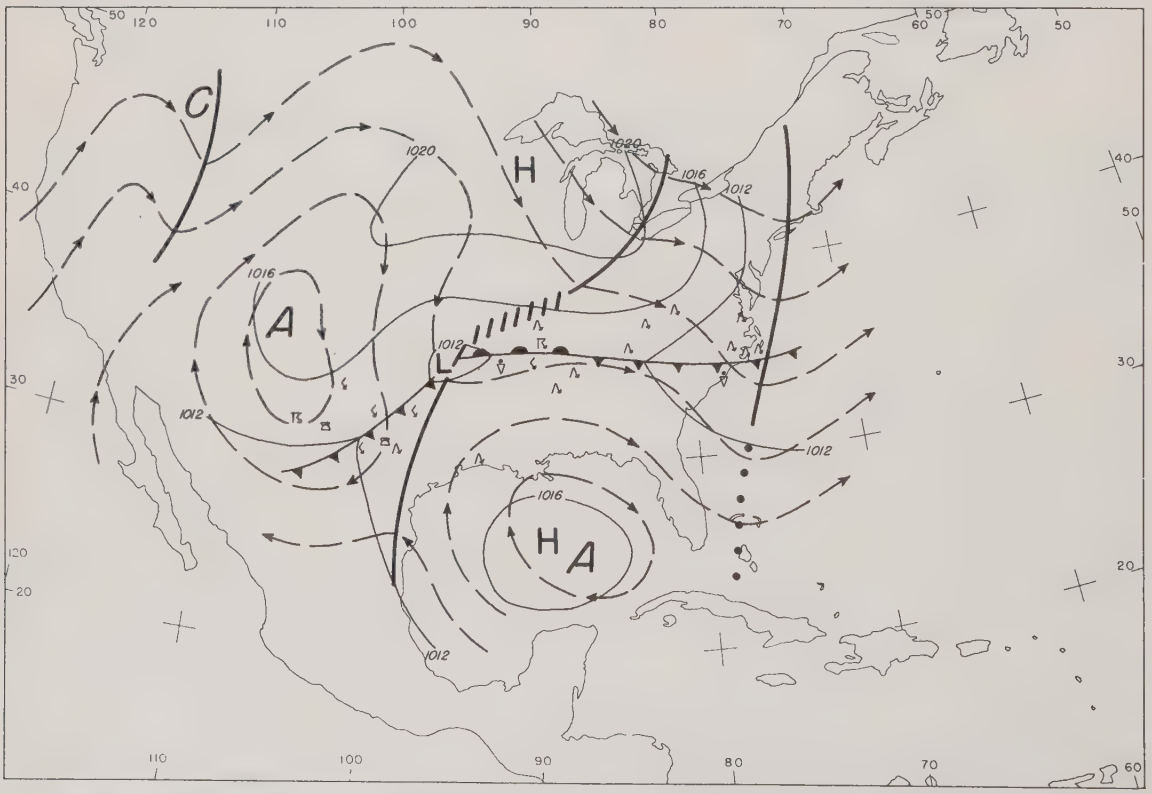

FIG. 9d.--Surface isobars, August 13, 1941, 0130 EST, and streamlines at 14,000 feet.

line which assumes the oblique position disintegrates with time, and the low-latitude section straightens up westward to become oriented N-S again (Figs. 8b, c; 9b, c). It also elongates into the higher latitudes when a new wave in the westerlies approaches. The straightening occurs necessarily in the northernmost part of the trough; consequently, the maximum mass convergence east of the straightening trough will be found in the region where the zonal wind is light or even westerly.

The greatest thunderstorm concentration, however, will not always occur there, as shown in Figure 8. In this case polar air had previously entered the central United States, and this prevented the convective activity. On August 12, 1941, however (Fig. 9), a frontal zone was present not far from where the straightening occurred. General thunderstorm activity, associated with deepening, broke out along the frontal zone.

Figures 8c and 9c show the completion of the sequence. The next wave trough in the westerlies had moved into a position almost due north of the retarded tropical trough, and the two troughs merged. Figure 9d illustrates a second breakoff which took place because the westerly pattern persisted. This interplay between high and low latitudes will repeat itself as long as moving westerly waves continue to dominate the flow over the United States.

At the East Coast a similar situation often prevails. The high-latitude section of a trough that has left its tropical part behind in Texas advances to the Atlantic seaboard and merges frequently with a wave in the easterlies that travels toward Florida from the Antilles. As the two waves approach the mean seasonal position of the polar trough, they both elongate to form a large-scale trough and a "subtropical breakthrough." A subtropical col then develops.

If no tropical wave is approaching, however, the high-latitude trough elongates itself into the tropics irrespectively and causes splitting of the subtropical high. The prevailing westerly or southwesterly winds over Florida veer toward northwest without passage of any disturbance. Simultaneously the Gulf high strengthens. Such a development (Figs. 9c, d; 14b), referred to as an "induced trough" (6), begins with preference about 1,000-1,200 miles east of the trough stationary in Texas, that is, just east of Florida. If the stagnant trough lies farther east, the induced trough also forms farther east.

The transformation that occurred between August 29 and 30, 1940 (Figs. 7c, d), presents an outstanding example of the corresponding sequence during a period of counterclockwise rotation. The polar trough that proceeded eastward in the South on the 28th and 29th collapsed late on the 29th as it lost

its orientation normal to the flow. The wave trough approaching the Gulf from the northwest then became the dominant feature. This second trough also lost its position normal to the flow aloft on August 30, especially in the north. As a result, it, too, disintegrated, and a third trough that advanced into the Great Lakes region became the dominant feature.

A crucial question remains: When should eastward passage of a wave in the westerlies along the Gulf Coast be predicted and when should stagnation be expected? This problem still offers some baffling aspects.[1] In general, however, the low-latitude perturbation will move eastward but little, if an anticyclonic shear prevails in the central and northern United States. A further criterion is the presence of upper northwesterly or northerly winds along the southern Atlantic seaboard and the existence of a separate high aloft over the Gulf and the southern Mississippi Basin. Predominance of a straight westerly current of considerable strength on the coast, however, and absence of considerable anticyclonic shear in the United States usually indicate that the disturbance will pass eastward, especially if counterclockwise rotation of the major centers in the United States takes place, as illustrated in Figure 7.

Termination.--The westerly pattern mostly gave way to frontal situations (cf. Table 7). A map such as presented in Figure 9d may easily lead to the establishment of the polar trough in its mean position, if there is no continued succession of waves in the westerlies. A position in the Mississippi Basin will follow a situation similar to that of July 14, 1940 (Fig. 8c). Such a development, however, is rare. The two instances of development of tropical patterns occurred when the westerly circulation was very weak and slowly disintegrated. The tropical systems arriving from the southeast found no resistance.

4. Fronts

The frontal days contributed greatly to the thunderstorm total of all stations (Table 11), with the highest relative thunderstorm frequency again at the coast. The inland stations were under the influence of stable polar air on numerous occasions when a front had passed there but stagnated somewhat farther south.

Practically without exception the subtropical and tropical parts of upper-air troughs lie to the east of the surface fronts, in outstanding contrast to the higher latitudes. This has been stressed previously by the author (6). Thus a latitude exists, variable in each situation, at which front and upper trough cross. As is clear from most illustrations in this report, this

[1]Further progress regarding this question has been made in more recent studies at the Institute of Tropical Meteorology.

TABLE 11

FREQUENCY OF WEATHER TYPES WITH FRONTS

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days.....	22	18	16	16	18	16
Per cent of all days without precipitation.....	7	8	11	9	6	6
Per cent of days in pattern with thunderstorms.....	65	65	40	40	70	40
Per cent of days in pattern with no precipitation.....	25	25	45	35	15	30

latitude is usually located north of the Gulf Coast in summer and at times even north of Latitude 35°. Southern stations thus tend to experience first the upper trough passage and then the frontal passage. Winds aloft will turn to northwest and north before the surface wind shifts (Fig. 11a). If front and trough are less than 100-150 miles apart, the greatest thunderstorm concentration occurs near the trough and dies out before the surface wind changes. Cumulus and stratocumulus and perhaps a few showers accompany the front itself. If front and trough are far apart, however, stations will experience two separate peaks of convection, one connected with the trough and the other with the front, with clearing between the two systems.

Special situations.--(a) When a situation favorable for a frontal advance southward has developed, the question arises just how far the front will go. The circulation that exists east of the front usually provides a good clue. If the flow aloft is westerly or becomes westerly with time, there is no obstacle in the path of the front. Rapid eastward motion follows.

Figure 10 illustrates such a case. A strong polar trough had reached the western Plains States on the evening of August 17, 1940, with some evidence of frontogenesis in the region where the surface isobars became more crowded. The surface picture was weak and quite confused. A shallow trough of low pressure extended from the Great Lakes region to southwest Texas. This trough, which had persisted for several days, originally contained fronts which disappeared prior to August 17 due to flow of air across the trough and modification of the original air mass contrast. Another shallow surface low lay near Cape Hatteras, associated with the lower latitude portion of a polar trough that had broken off from the high-latitude part, as described in the previous chapter. The thunderstorm activity, greatly reinforced by diurnal convection, was concentrated near the two upper and surface troughlines.

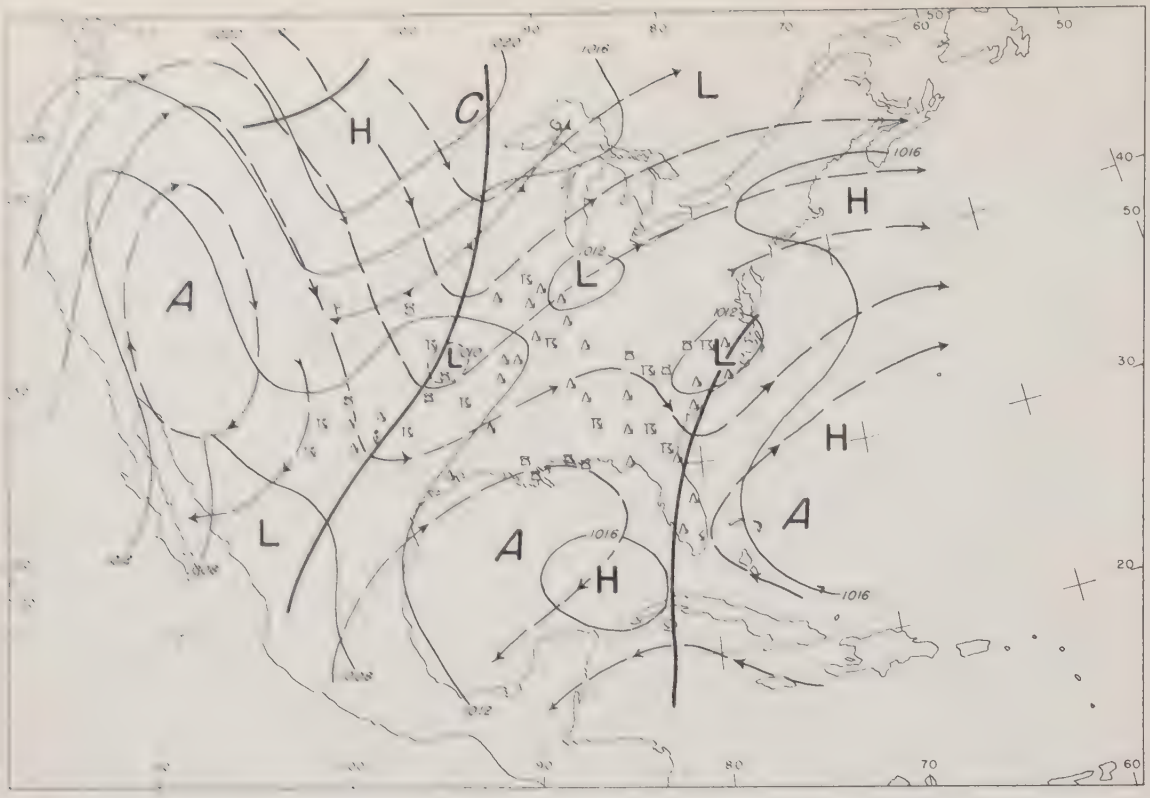

FIG. 10a.--Surface isobars, August 17, 1940, 1930 EST, and streamlines at 14,000 feet.

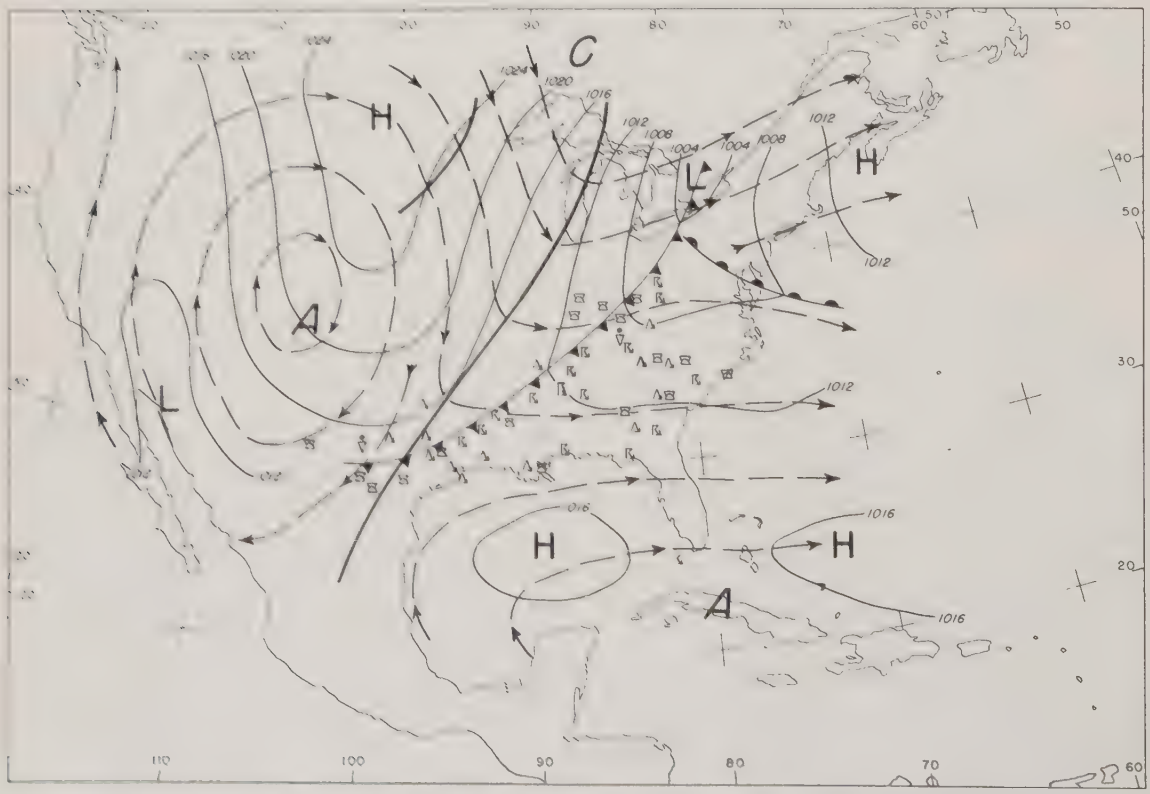

FIG. 10b.--Surface isobars, August 18, 1940, 1930 EST, and streamlines at 14,000 feet.

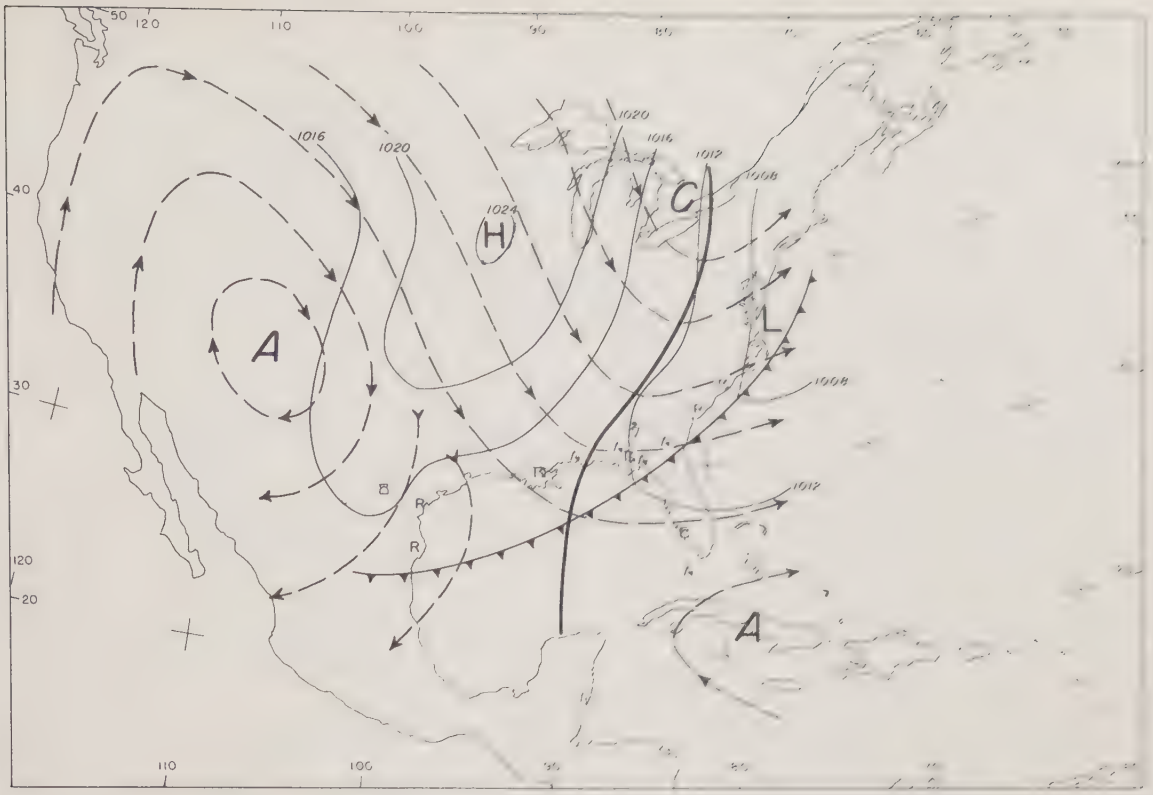

FIG. 10c.--Surface isobars, August 19, 1940, 1930 EST, and streamlines at 14,000 feet.

In addition, scattered thunderstorms occurred over a wide area of the South during the afternoon.

The arrival of the strong western trough ended the stagnant situation. The Bermuda High was well out to sea, and there was no resistance to the eastward advance of the upper trough. The front which lay almost normal to the upper flow was carried along. On August 18 the thunderstorms were mostly concentrated along the front, and thunderstorm activity had become much heavier in the South. As is evident from a comparison of Figures 10b and 10c, the activity ceased with the frontal passage excepting some thunderstorms which persisted near the upper troughline. The latter was to the west of the surface front even on the coastline, a clear indication of how wintry a weather situation existed along the Gulf Coast in mid-August, 1940.

When the fronts stretch from Florida to Mexico, they lie nearly parallel to the upper winds because of their E-W orientation. Motion then ceases, and rapid air-mass modification and re-establishment of the anticyclonic circulation aloft ordinarily produce a quick disintegration. In southern Texas the disturbed weather can continue for several days both south and north of the weakening front. This is especially true if southeasterly winds re-establish

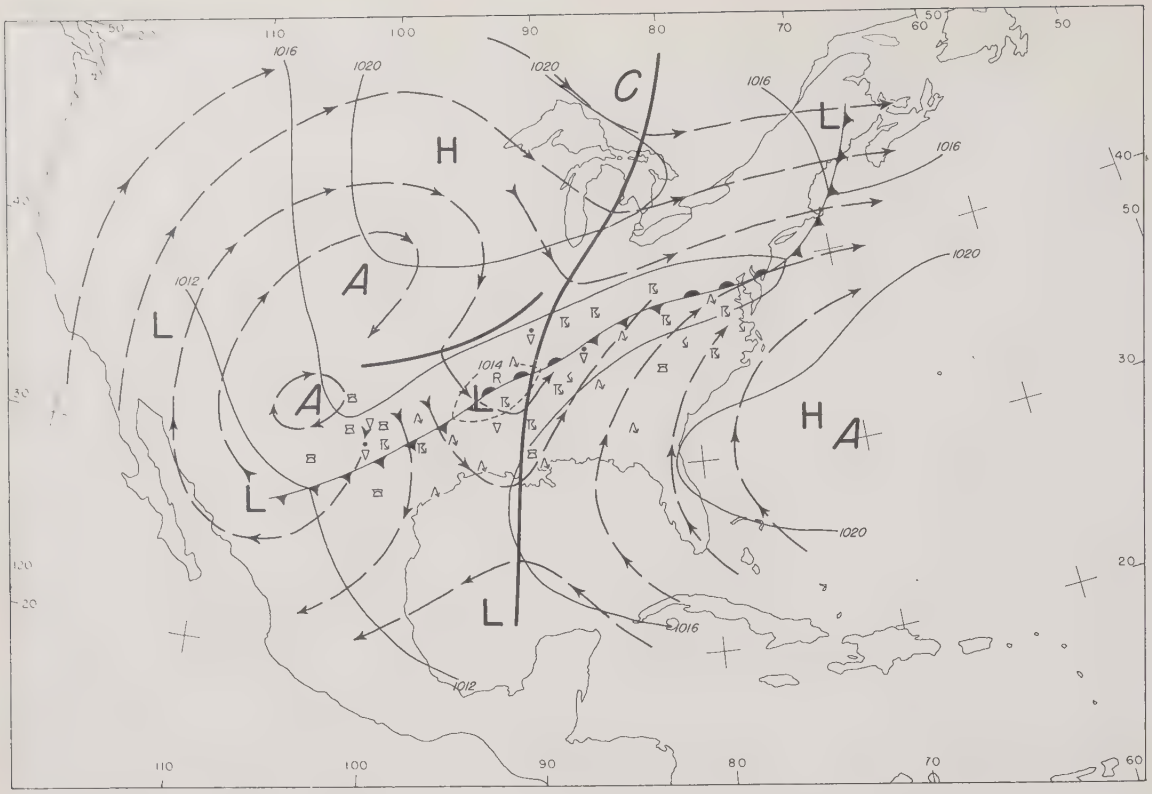

FIG. 11a.--Surface isobars, July 3, 1941, 1930 EST, and streamlines at 14,000 feet.

themselves near Brownsville, while the front is still active. If a wave in the easterlies then arrives from Yucatan, the weather can become quite severe (September 8-10, 1943). The front, reinforced by the tropical wave, begins to move westward and northwestward. Because of the disappearance of air-mass contrasts, the whole system then takes on the appearance of a wave in the easterlies.

b) If a warm high is centered in the western Gulf as a cold front approaches the western Gulf stations, southerly and southwesterly winds prevail there which retard the frontal motion southward west of the Mississippi. The front, however, retains its ability to move southward east of the high where the upper winds are northwesterly and northerly. The original NE-SW orientation of the front then changes quickly to E-W and even SE-NW as the eastern section reaches the Gulf Coast west of the Florida peninsula, while the western part remains stalled in Oklahoma, Missouri, and Arkansas.

If the trough aloft connected with the frontal advance travels quickly into the ocean past the East Coast, southwest winds aloft will soon reappear in the Middle West and cause the portion of the front located there to disintegrate or to move northward. If the trough stalls in the East, however,

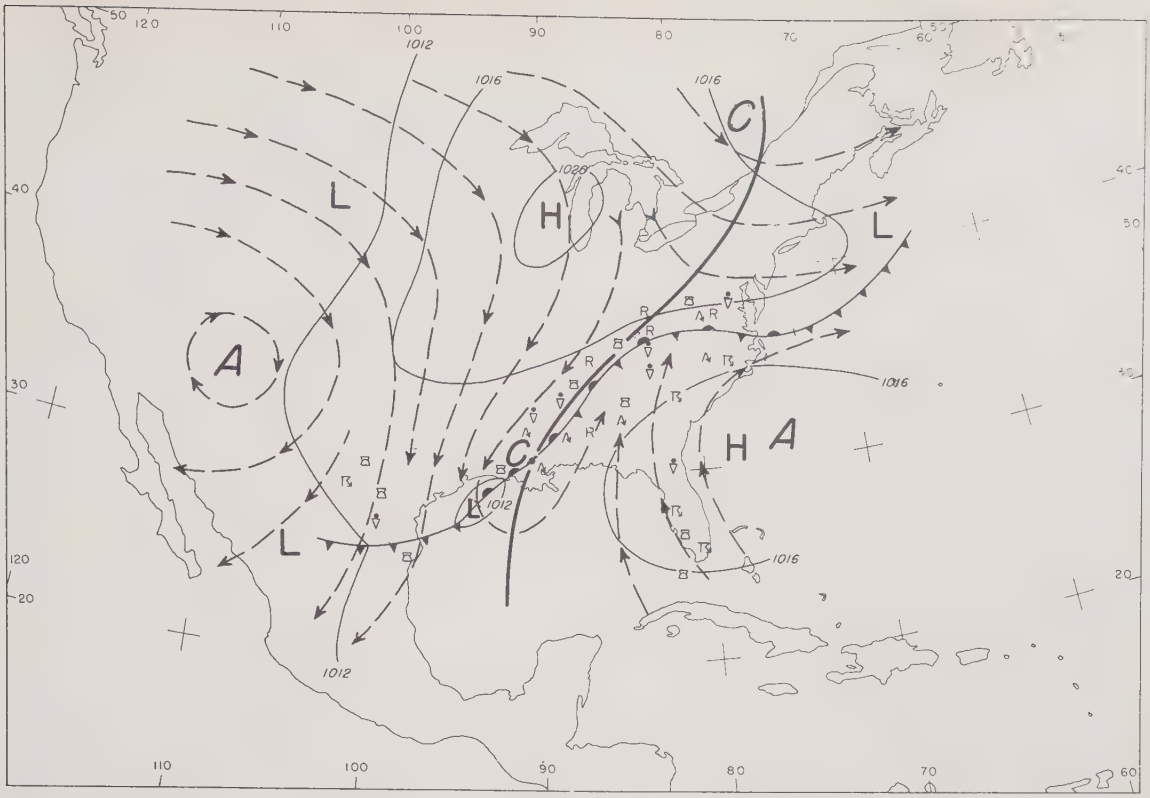

FIG. 11b.--Surface isobars, July 4, 1941, 1930 EST, and streamlines at 14,000 feet.

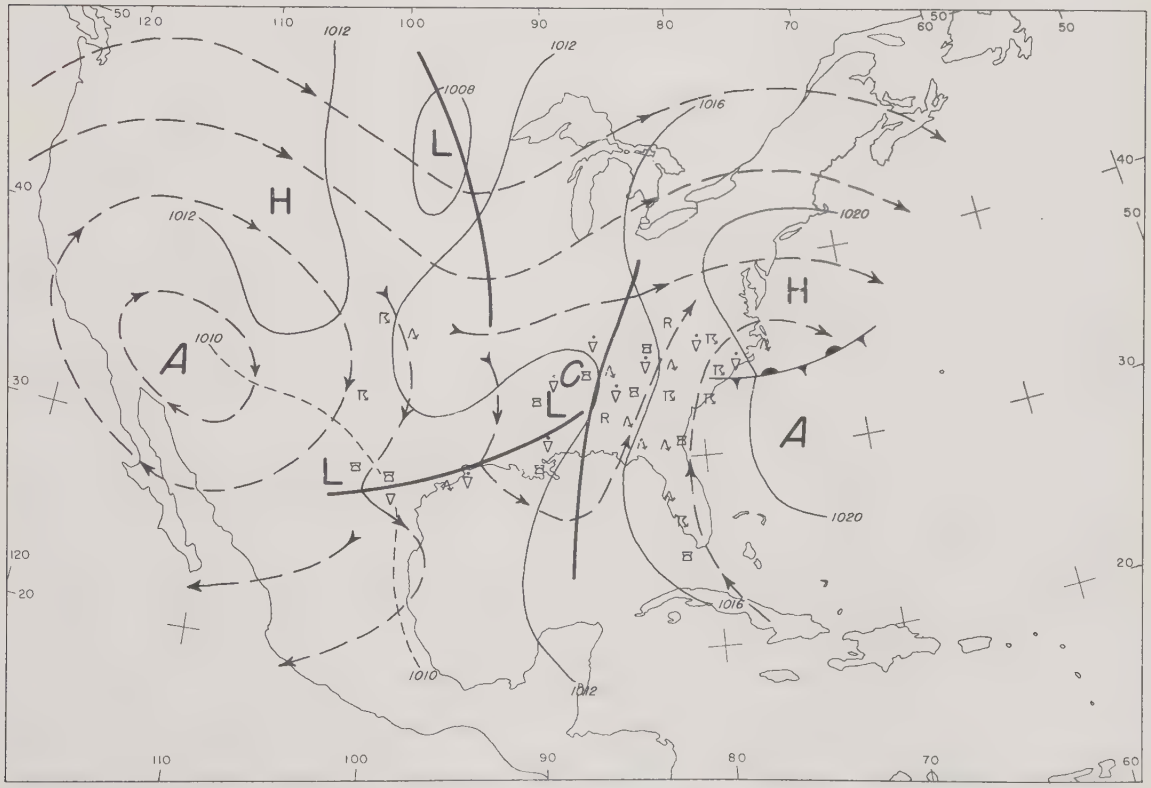

FIG. 11c.--Surface isobars, July 5, 1941, 1930 EST, and streamlines at 14,000 feet.

north and northeast winds aloft tend to develop in the central United States, and the front slowly pushes southward. This event leads to "meridional highs," unless new waves in the westerlies follow rapidly. Within 24 hours or less after the original polar trough that initiated the frontal motion has bypassed the front, a new upper trough, oriented nearly parallel to the front, will develop over or just north of the front. This new trough will form with preference from a NW trough that moves into the area and deepens. If no such trough approaches, however, a streamline deformation will appear in situ and will exercise a dominant influence on the southern weather within a short time. Figures 8b and 8c give some indication of such a development in the Southeast.

c) A third variation of the frontal displacement occurs when the front has a free path southward in the western Gulf region but is blocked east of the Mississippi. The Bermuda High then extends well into the southeastern United States (Fig. 11a).

Fronts will regularly stall in the vicinity of New Orleans, and organized convection that may be severe is likely to persist there for several days. Deepening may result along the stalled front, as indicated in Figure 11b, unless further waves in the westerlies interfere. Because of the presence of the front on July 4-5, 1941, the deepening manifested itself at first as a surface depression on the front that initially traveled slowly northeastward. Coincident with the disappearance of the westerlies to the north, however, this movement soon ended (Fig. 11b). The center became stagnant and persisted mainly in the upper air. The surface wind-shift line on July 5, 1941 (Fig. 11c), could not be called "front" any more because of continuous air motion through it. It was mainly a reflection of the trough aloft.

A situation such as illustrated in Figure 11 will break up, if the westerlies increase and carry the upper low northeastward. A gradual eastward displacement of the upper anticyclone in the United States, however, will produce steady easterly or southeasterly winds along the Gulf Coast. The low in that case begins to drift northwestward.

5. Waves in the Easterlies

All stations received 10 per cent or slightly more of their thunderstorm total when they were mostly under the influence of a tropical wave (Table 12). The percentage of dry days increased from the coast northward. The relative frequency of thunderstorm days nowhere was very great and diminished northward toward the subtropical ridge line. Shower activity, however, was considerable at all coastal stations, similar to events in the Antilles during wave passages. The recorded precipitation may total several inches per day with very limited thunderstorm activity.

TABLE 12

FREQUENCY OF WEATHER TYPES WITH WAVES IN THE EASTERLIES

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days	12	10	12	10	10	12
Per cent of all days without precipitation	5	6	9	9	6	8
Per cent of days in pattern with thunderstorms	50	50	35	35	60	40
Per cent of days in pattern with no precipitation	30	30	60	55	20	50

Special situations.--(a) The frequency of wave passages lessens from south to north, although in rare instances waves may appear at the Middle Atlantic coast and even south of the Great Lakes region. If westerly flow prevails in the north and the subtropical ridge is situated north of the coast, waves will travel westward through the Gulf and affect only southern Texas and Mexico. If the polar trough is well developed near its mean position, they will arrive at Brownsville from the south and southeast. Although often it is almost impossible to locate them in the upper wind field north of Tampico, their moist layer will continue to move with the wind. Evidently, as mentioned before, it is of importance to trace these moist layers and time their arrival at the coast line.

b) If a broad easterly current which extends to at least 20,000 feet dominates the coast, the waves have a structure similar to that observed in the trade-wind belt. This is especially true if the easterly current reaches as far as New Mexico and does not acquire a large southerly component of motion over Texas prior to the arrival of the wave trough. Air columns initially located east of the troughline gradually approach the latter, curving counterclockwise. Convergence and shower activity predominate east of the troughline and clear skies to the west of it.

Commonly, however, there is a large anticyclonic shear in the easterly current north of the coastline. A band of maximum east winds exists that weakens both northward and southward. As previously stated in this report, precipitation is likely to develop in the area where the winds are strongest, including the region west of the troughline. There, however, cumulonimbus formation is uncommon, and precipitation tends to occur in the form of steady rain. The thunderstorms begin after passage of the troughline.

North of the belt of strong easterlies, there should be a rapid reversal

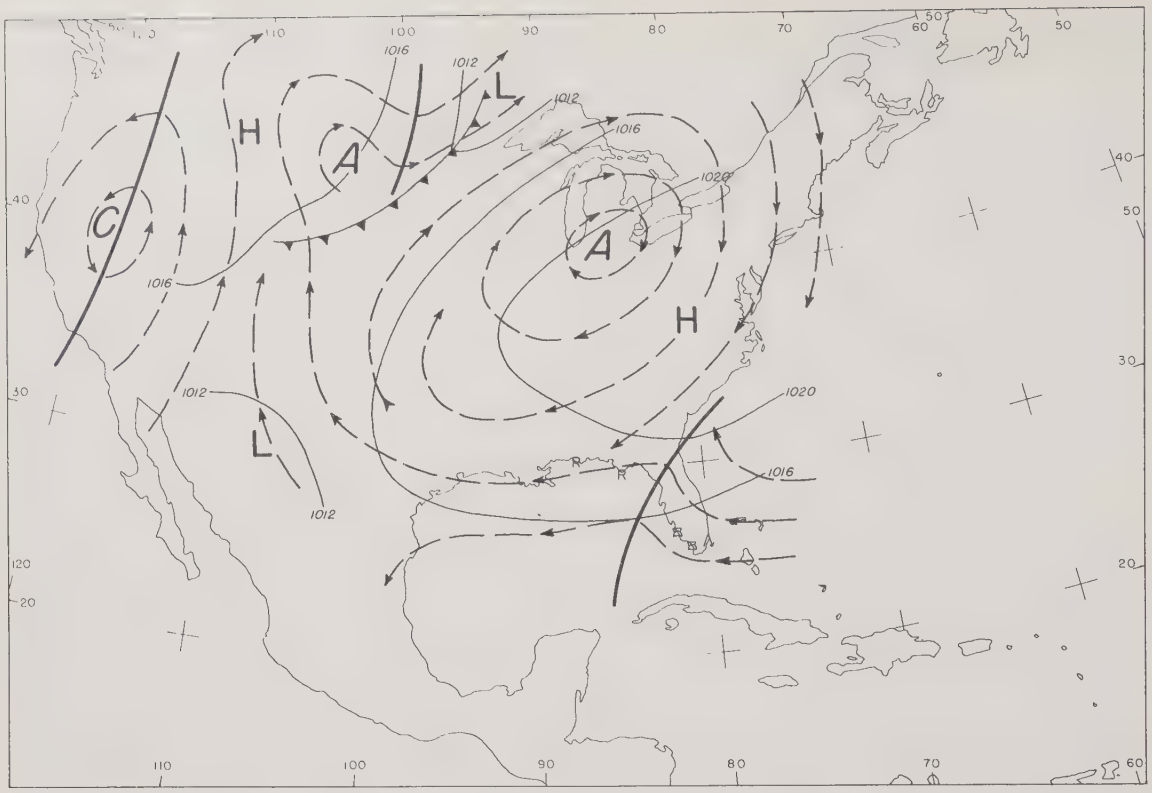

FIG. 12a.--Surface isobars, September 20, 1940, 0130 EST, and streamlines at 10,000 feet.

from cloudy to clear conditions, especially west of the wave trough. Remarkable cases with such a weather distribution did occur in the central and western Gulf areas. North of the coast the South remained entirely clear as a wave passed westward over the Gulf of Mexico, and the coastal easterlies aloft were unusually high--40-50 mph--although no tropical disturbance was forming. Ships just south of the coast reported squally weather, and Corpus Christi and Brownsville experienced prolonged rain and shower activity before and after the wave passage.

The wave illustrated in Figure 12 increased in intensity and size during its westward motion. The bad weather, initially distributed about equally on both sides of the wave trough, later became heaviest on the eastern side. Although rain was mostly reported at midnight on September 22, 1940 (Fig. 12c), rainfall totals of over 3 inches at several stations in Texas indicated the convective character of the precipitation to the rear of the trough. Its axis slowly rotated counterclockwise, and a tropical storm moved from Yucatan into the Gulf of Mexico late on September 22. The rainfall in the United States on the 21st and during the morning of the 22d, however, was not attributable to this disturbance.

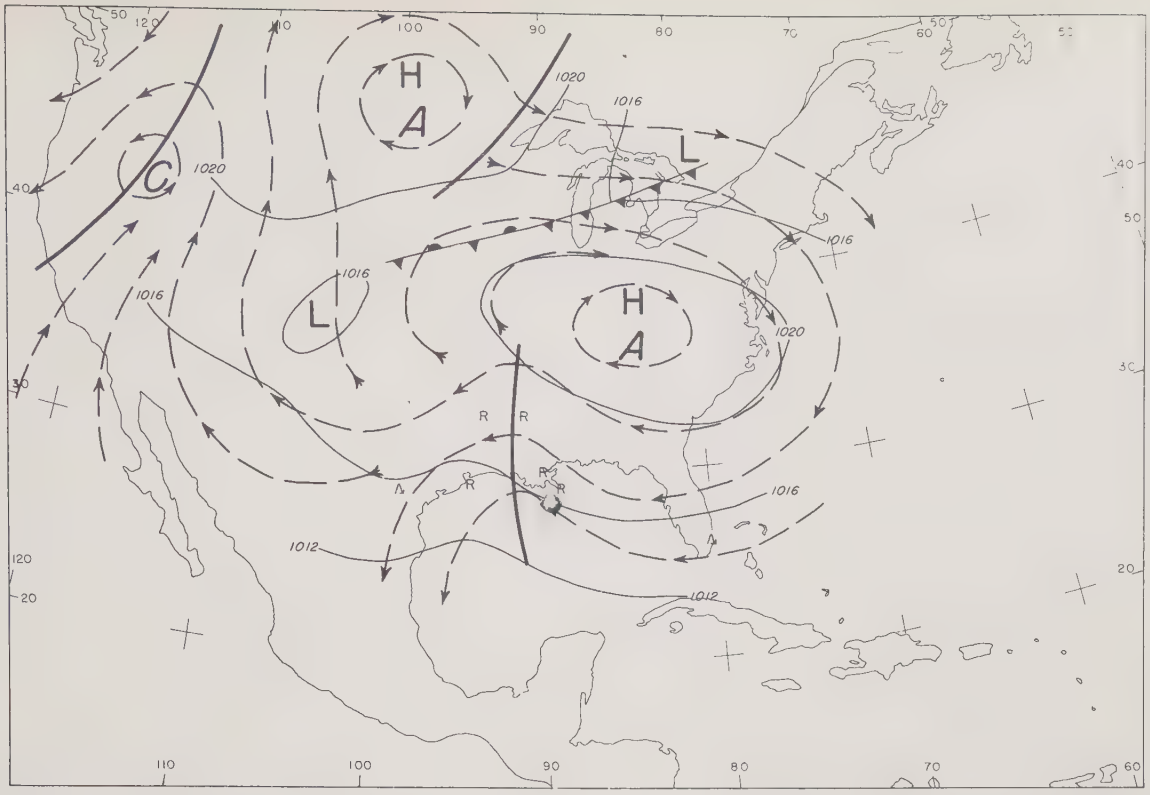

FIG. 12b.--Surface isobars, September 21, 1940, 0130 EST, and streamlines at 10,000 feet.

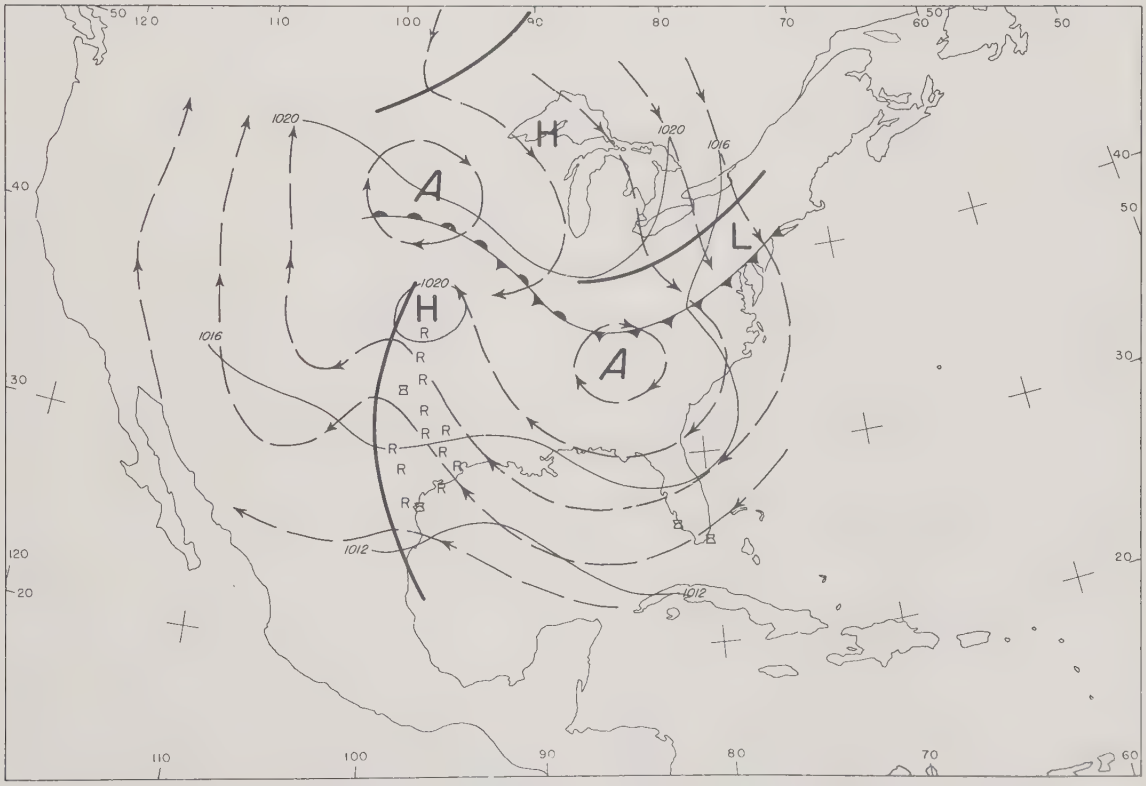

FIG. 12c.--Surface isobars, September 22, 1940, 0130 EST, and streamlines at 10,000 feet.

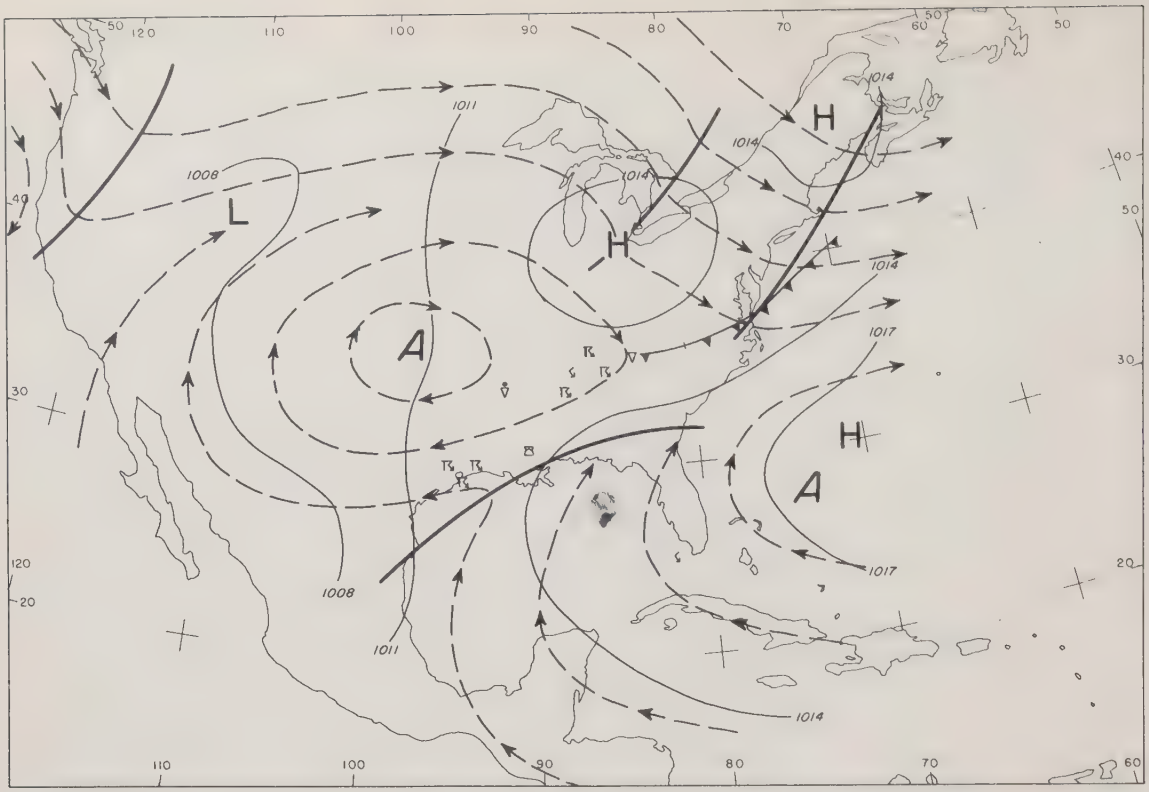

FIG. 13a.--Surface isobars, August 11, 1943, 0130 EST, and streamlines at 10,000 feet.

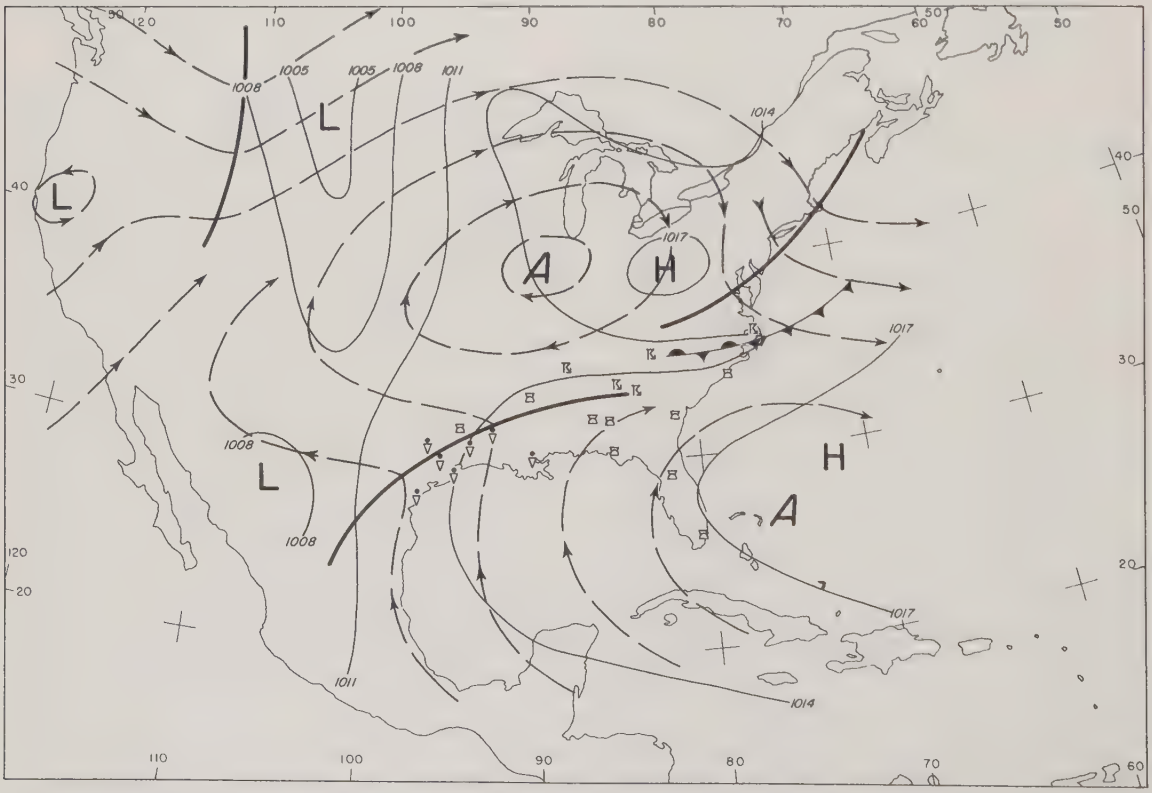

FIG. 13b.--Surface isobars, August 11, 1943, 1330 EST, and streamlines at 10,000 feet.

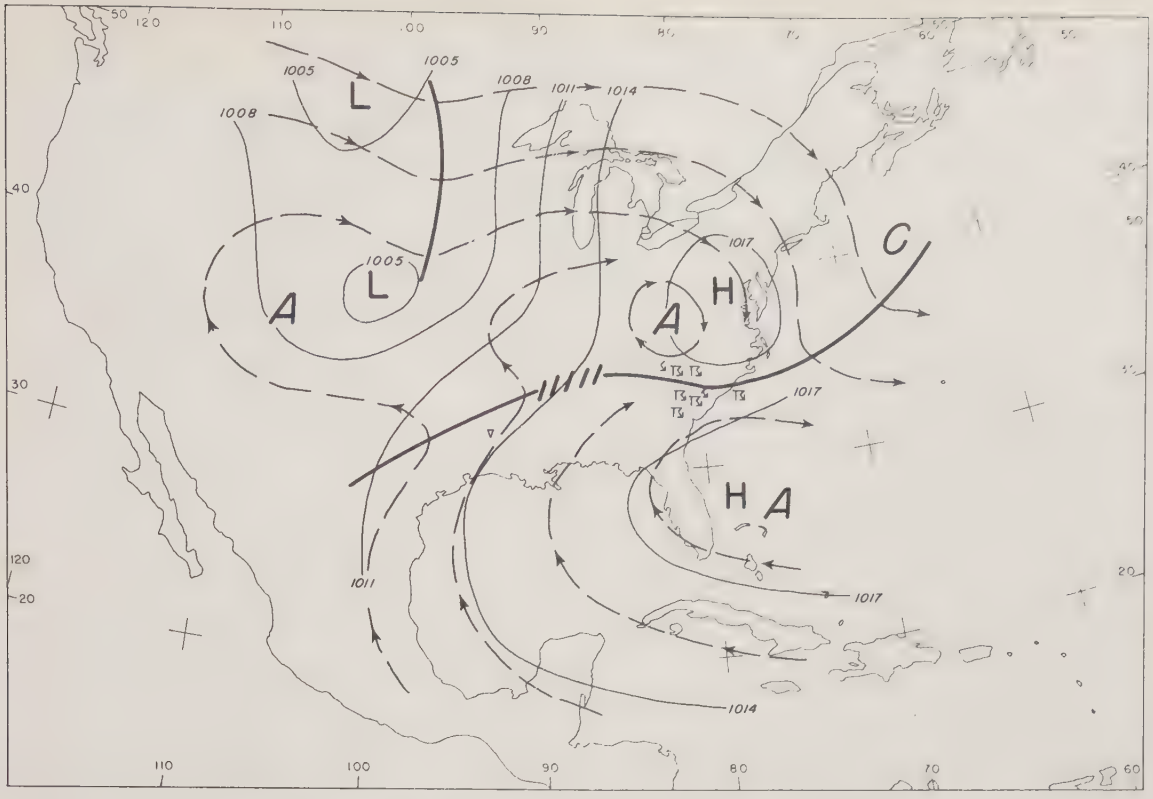

FIG. 13c.--Surface isobars, August 12, 1943, 0130 EST, and streamlines at 10,000 feet.

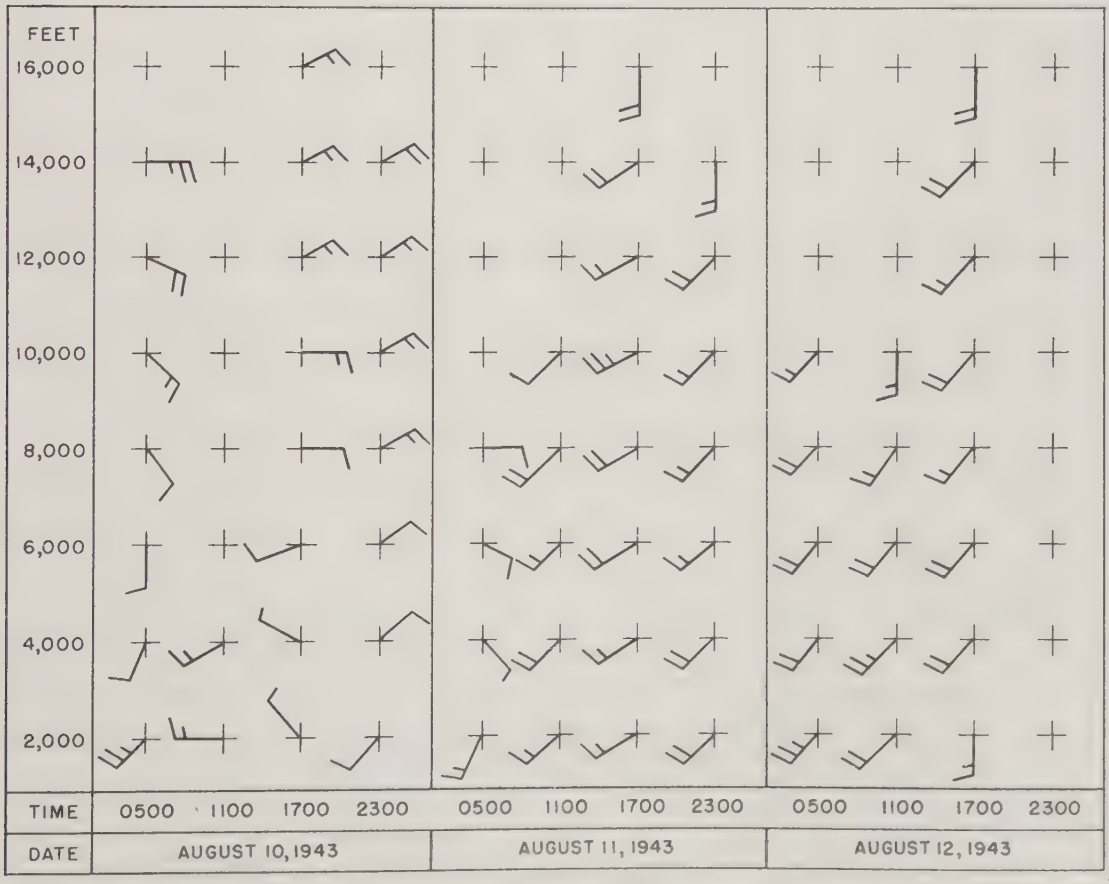

FIG. 13d.--Time-section of the upper winds at Houston, Texas, August 10-12, 1943.

c) One wave passed westward when dry polar air was settling on the coast following a frontal situation. There was no bad weather at all on either side of the wave trough. Waves that strike a still active front, however, may produce severe convection and thunderstorms. The winds near the ground are then northeasterly and those aloft southeasterly. The wave trough overlies the front, and intense overrunning results. Indeed, when a wave approaches with a NE-SW orientation rather than N-S, a field of motion very favorable for frontogenesis exists along the troughline, especially if the winds over the United States are northeasterly. Several waves became well-marked warm fronts under such circumstances and the weather associated with them deteriorated greatly.

d) If a warm high is centered over the eastern United States, waves that advance westward from Florida find southeasterly and southerly winds west of New Orleans. They then die out rapidly, as the northeasterly current ahead of the trough is obliterated. The moist layer, however, will carry on and may reach the westerlies still intact. One such moist layer, traveling eastward in the westerlies, produced thunderstorms all the way from Oklahoma to Washington, D.C., where it left the field of observation. Another struck a cold front which moved down the Atlantic seaboard, and heavy thunderstorms resulted.

e) Finally, there are instances, previously mentioned, when a wave in the easterlies approaches a large-scale polar trough. The amplitude of the polar trough and its bad-weather zone increased in every such case observed during the study, and several closed low centers formed in the trough south of the subtropical col. An interesting variation occurs if the broadscale trough is oriented NE-SW rather than N-S. Juncture of the polar trough and the wave in the easterlies may then result in the development of a shearline of the type described in the next chapter, if the combined system continues to advance northwestward and northward. The period of August 11-12, 1943 (Fig. 13), presents such a case. A wave in the easterlies, previously described by the author (6), combined with a polar trough that extended from the Bahamas to Yucatan. After some stagnation the system reached the Gulf Coast on August 11.

Termination.--The number of waves that deepened and produced a tropical disturbance was considerable and presence of a wave in the Gulf always indicates danger (cf. Table 7). Once a low aloft rather than a tropical storm formed. This took place just north of the coast line, and, as is customary in such instances, the intensity of the surface center remained small.

6. East-West Shearlines

The large number of east-west shearlines encountered during the study constituted one of the major surprises. Although only a relatively small number of days were labelled "shearline days," such systems played an auxiliary part on numerous occasions when the flow was mainly governed by other systems (cf. Figs. 4, 7, 9, 13).

Except at Fort Worth, the percentage of thunderstorm days is very great and the percentage of dry days small (Table 13). The widespread convection attending the shearlines is even more emphasized by the relative thunderstorm frequency. Galveston, Houston, and New Orleans will have thundershowers almost with certainty when the shearline is in their vicinity. At Shreveport and Vicksburg the dry days occurred mainly when the shearline was still a good distance south of the coast.

The frequent appearance of two distinct anticyclonic centers aloft on the same meridian represents one of the most important deviations of the summer-time field of motion from winter. The meridional arrangement follows perhaps with greatest frequency the clockwise rotation of the subtropical cols and more rarely the counterclockwise rotation.

Quite generally it may be stated that upper highs whose longest symmetry axis is oriented N-S persist but rarely and that they will tend to split into smaller anticyclonic cells. The dimensions of these cells are dependent at least partly on the extent and strength of the meridional currents on both sides of the elongated ridge. Their radius varies from 5° to 10° of latitude. With strong northerly currents of about 50 mph along the East Coast at 10,000-15,000 feet, the radius approached 10° in several instances, whereas with winds of only 15-20 mph it was closer to 5°. The splitting usually began when a NW trough was moving down the East Coast. This trough, oriented nearly E-W, elongated westward with time until splitting of the upper high was completed. The "induced" portion of the trough then became stationary and did not continue southward and southeastward with the eastern section. It may be added that if one large upper high is found at 10,000 feet, comparable in size to the surface oceanic cells, splitting of this high into at least two separate centers follows almost with certainty within 1-2 days.

The two meridional cells stand out on upper-wind maps because of the large wind shear of nearly 180° between them. This shearing zone represents a marked though often narrow zone of convergence in which thunderstorms will readily break out, given suitable initial air-mass characteristics. As the shearline broadens westward, the thunderstorms also spread in that direction. Thus, in the westerly current south of the line, the forward edge of thunder-

TABLE 13

FREQUENCY OF WEATHER TYPES WITH EAST-WEST SHEARLINES

Type	GS	HU	FV	ZH	NO	VS
Per cent of all thunderstorm days	12	13	7	14	10	14
Per cent of all days without precipitation	2	1	8	3	2	4
Per cent of days in pattern with thunderstorms	70	85	25	65	80	65
Per cent of days in pattern with no precipitation	15	10	70	35	10	35

storm activity will advance against the prevailing wind.

Completion of the splitting demands stationary broad scale conditions. These are given by a large streamline amplitude indicated by the elongated ridges. An increase of the westerlies quickly stops the development and induces the northern high to shrink and recede southeastward. Whenever the synoptic situation leads to expansion or shrinkage of only one of the highs, the smaller high will begin to rotate clockwise about the larger one.

Special situations.--(a) The shearlines commonly progress northward and only rarely will they move south for a protracted distance. Passage of a pronounced westerly trough through the United States and equatorward spreading of the polar westerlies will cause a southward retreat, if the shearline is initially located over the Gulf. The retrogression may carry it beyond Yucatan into the Caribbean. Weakening, however, will take place during such displacement.

Usually the northward motion will be negligible, while an upper high remains stagnant north of the shearline (Fig. 14). As soon as the high gives way eastward, however, or if the entire high moves northward, the shearline accelerates and advances inland. Its speed did not exceed 15 mph in any of the cases observed, and it usually was less than the southerly wind component normal to it. Air thus kept moving through the line from south to north. The latter, therefore, was not an air-mass boundary, although it can be seen readily that a combination of a shearline with a front stagnating near the coast will result in a powerful frontal system.

Although the heaviest convection usually appeared south of the line, the thunderstorm activity had a tendency to cease rather quickly after its passage, because subsidence developed in the high to the south. Northward advance of the shearline also opened a free path for succeeding waves in the easterlies, and, when such waves followed this path, prolonged convection

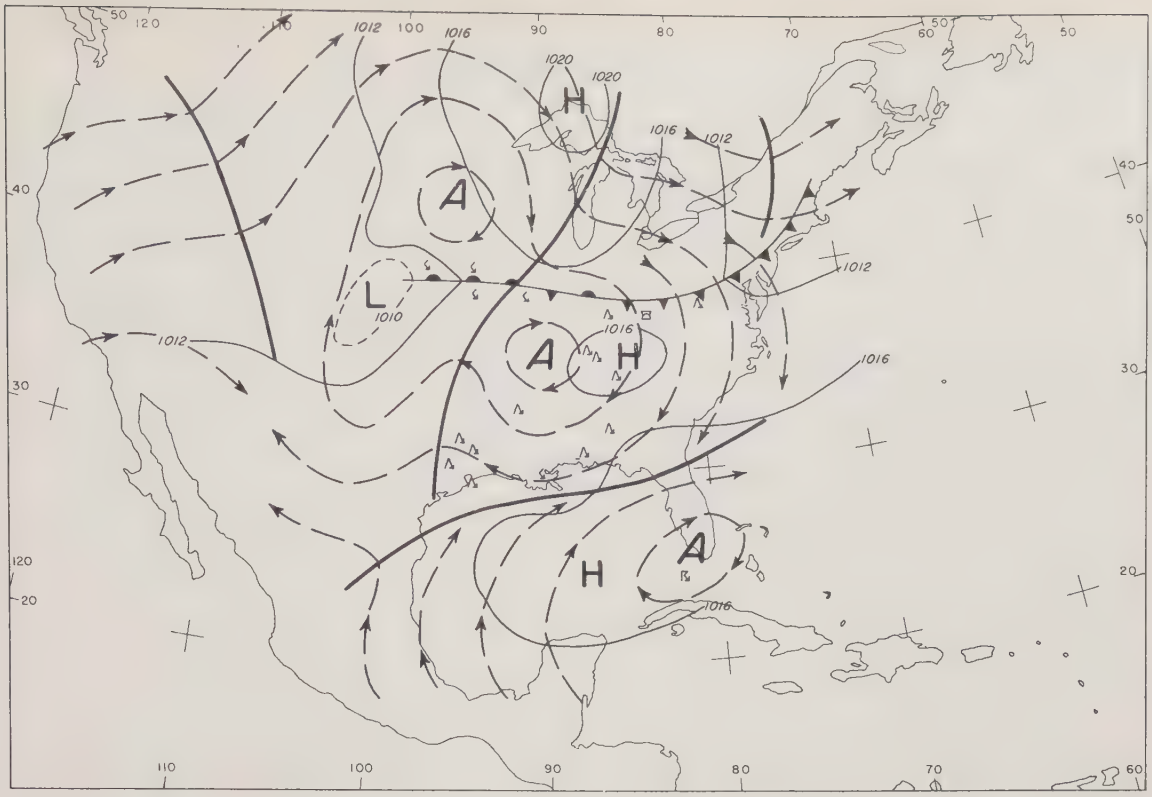

FIG. 14a.--Surface isobars, July 31, 1940, 0130 EST, and streamlines at 10,000 feet.

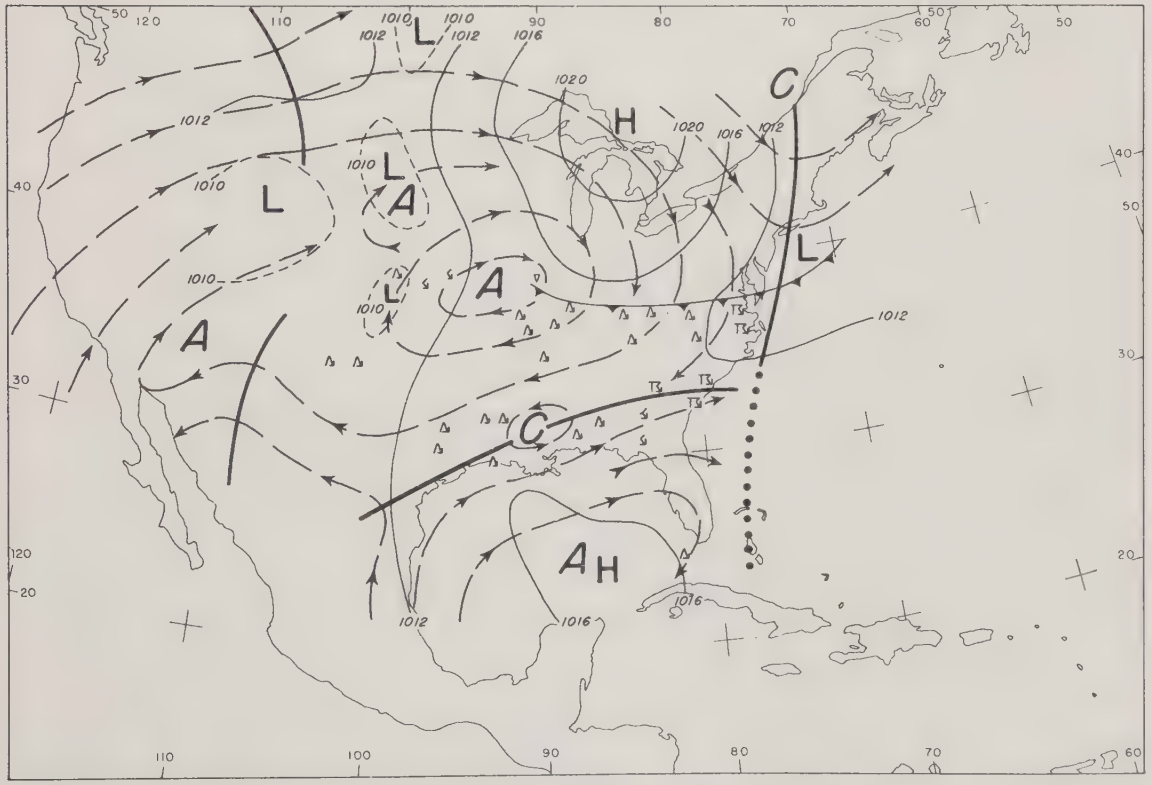

FIG. 14b.--Surface isobars, August 1, 1940, 0130 EST, and streamlines at 10,000 feet.

occurred south of the shearline (June 11-13, 1943).

b) Because of the extreme cyclonic turning of the wind across the shearline, one or more closed vortices will usually be situated along the line, which offers an excellent opportunity for the development of unstable waves (Fig. 14b). A special concentration of convective activity accompanies these centers. If there is a strong anticyclonic shear north of the coast line, the vortices will die quickly when the shearline comes inland. Otherwise intensification is likely, in particular when a triple point forms between the shearline and a polar trough. Many hurricanes form in connection with the shearlines whose characteristics are remarkably like those of the "equatorial front."

Figure 14 illustrates a case of cyclogenesis and quite generally brings out the complications that are possible in the subtropical summertime wind field. A polar trough advanced eastward on July 31, 1940, when a very well-marked shearline lay just south of the Gulf edge. The polar trough then split in accordance with the principles previously noted. The northern part proceeded to the East Coast and elongated again into the tropics. Thus, the cold front which had been blocked in the Middle West was free to move down the Atlantic seaboard. On August 2 only a low-pressure trough rather than a front remained.

The low-latitude part of the polar trough advanced westward into the southern Rockies. There it was stopped by the arrival of new waves in the westerlies from the northwest. Coincident with the southward spreading of the polar westerlies over the Rockies, the easterly circulation near the wave trough reversed to westerly along the northern part of that troughline.

Passage of the polar trough and northeastward advance of the warm high in the Midwest to its rear, permitted the shearline to cross inland on August 1. The small low center in the lower Mississippi Basin traveled westward. Coincident with the increase of anticyclonic shear to its north on August 2, it weakened as it reached eastern Texas and there appeared mainly as a cyclonic streamline deformation.

A blocking situation persisted on the East Coast. The West Atlantic polar trough and the southern shearline had formed a triple point just east of Florida and the Carolinas Deepening began on August 2 and continued on August 3, when a NW trough which moved down the East Coast joined the "triple point." An upper low formed and started to move westward guided partly by easterlies to its north. Along the Carolina coast upper winds shifted from north and northeast to southeast.

Undoubtedly the portion of the Atlantic polar trough shown in Figures 14c and 14d had broken off from its high-latitude part on August 2. The westward motion of the upper low center then was also due to the interplay

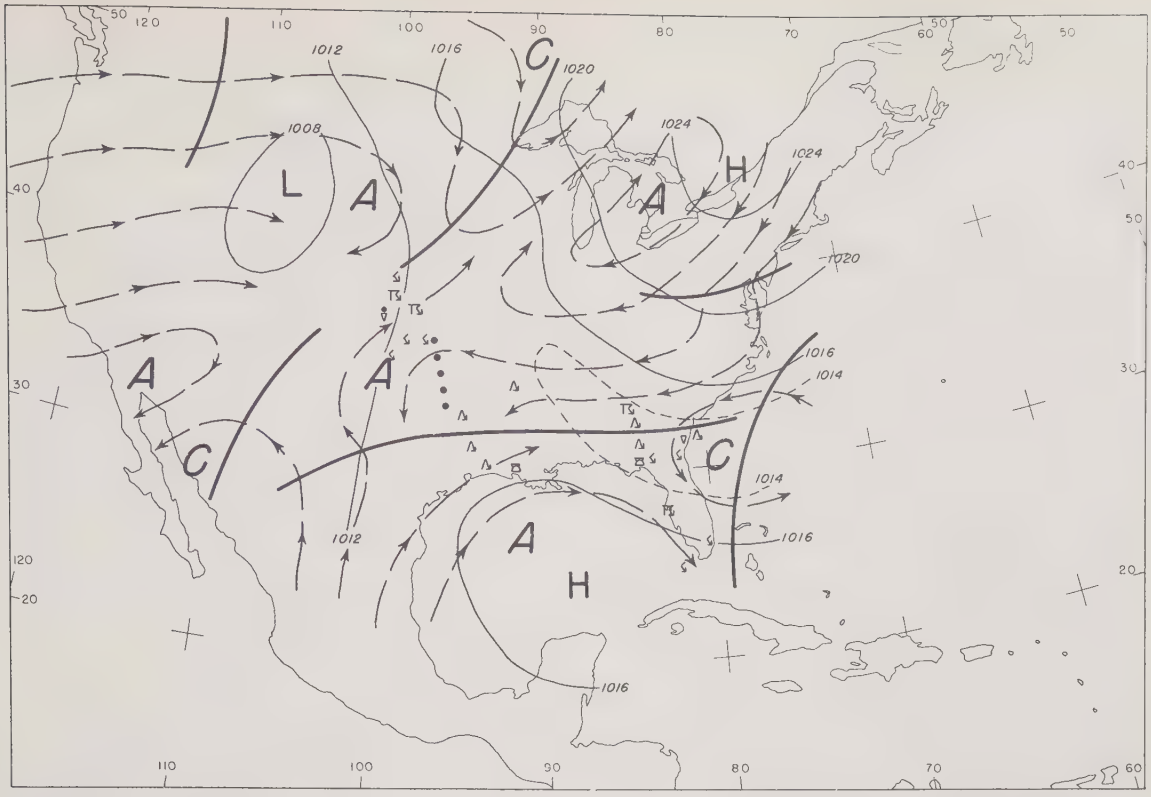

FIG. 14c.--Surface isobars, August 2, 1940, 0130 EST, and streamlines at 10,000 feet.

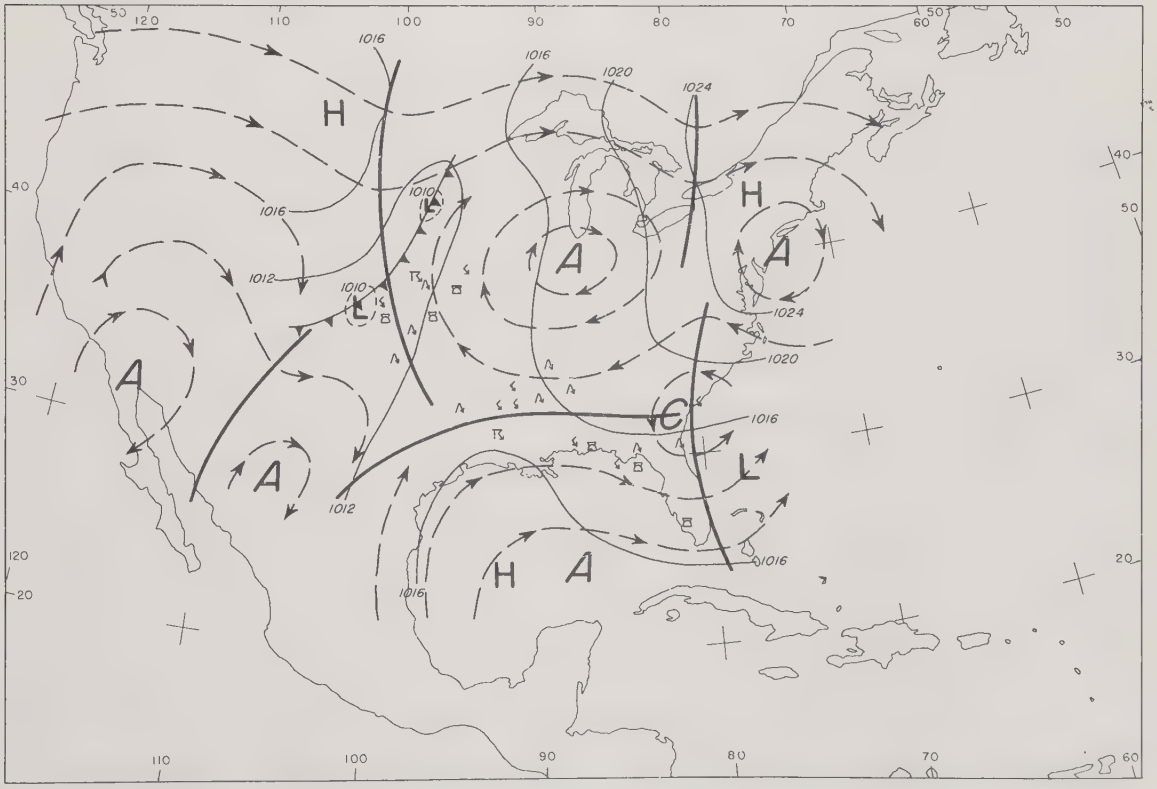

FIG. 14d.--Surface isobars, August 3, 1940, 0130 EST, and streamlines at 10,000 feet.

between high- and low-latitude troughs so frequently stressed in this report. After the breakoff the low-latitude section moved westward and tended to assume a more N-S orientation, as is clearly indicated on August 3. The strong northern trough that approached the Great Lakes area from the West on August 2 was not able to advance eastward except in the far north because of the dynamic high to the east of it. The section of the trough located over the eastern Great Lakes area in Figure 14d represented a new elongation southward, as a subtropical breakthrough developed in the eastern United States, which joined the northern and southern troughs and further intensified the low center over South Carolina. Two subtropical cols were present, one located over Cuba and the northern Caribbean and the other at a very high latitude near Pittsburgh.

The upper low subsequently continued to travel southwestward into the Gulf of Mexico and there attained hurricane strength at the surface.

7. Closed Lows Aloft

Three tropical storms that moved inland during the period studied did not continue into the higher latitudes at once but stagnated near the coast. The surface centers, as usual, diminished rapidly, while the upper circulation retained or even increased its intensity. One upper low was brought in by a shearline in a situation similar to that of Figure 14b. Most of the other lows were generated near the coast.

Closed cyclonic circulations aloft are generally known as sources of disturbed weather. Difficulties arise, however, in predicting the width of the bad-weather zone to be expected and the type of precipitation. Shreveport and Vicksburg, for instance, experienced many days with rain but without thunderstorms. Modified polar air near the ground or fairly stable air aloft was then present. Convergence and stretching of the air columns in the vicinity of a moving upper center regularly takes place in the lower and middle troposphere. If stable air columns are involved, stratiform clouds and steady precipitation result.

A very slowly moving or quasi-stationary center presents another problem. In such a case streamlines and trajectories become almost identical. The same air columns remain near the low. Continuous overturning of these columns eventually leads to a uniform lapse rate everywhere near the center, and the potential energy of the atmosphere due to lack of thermodynamic equilibrium vanishes. Thus, approximately within a day after stagnation started, active convection ceased inside of two such low centers that became stagnant during the period studied. Rather fair weather prevailed with broken middle and high clouds and only occasional light rains or showers. In the outskirts of the

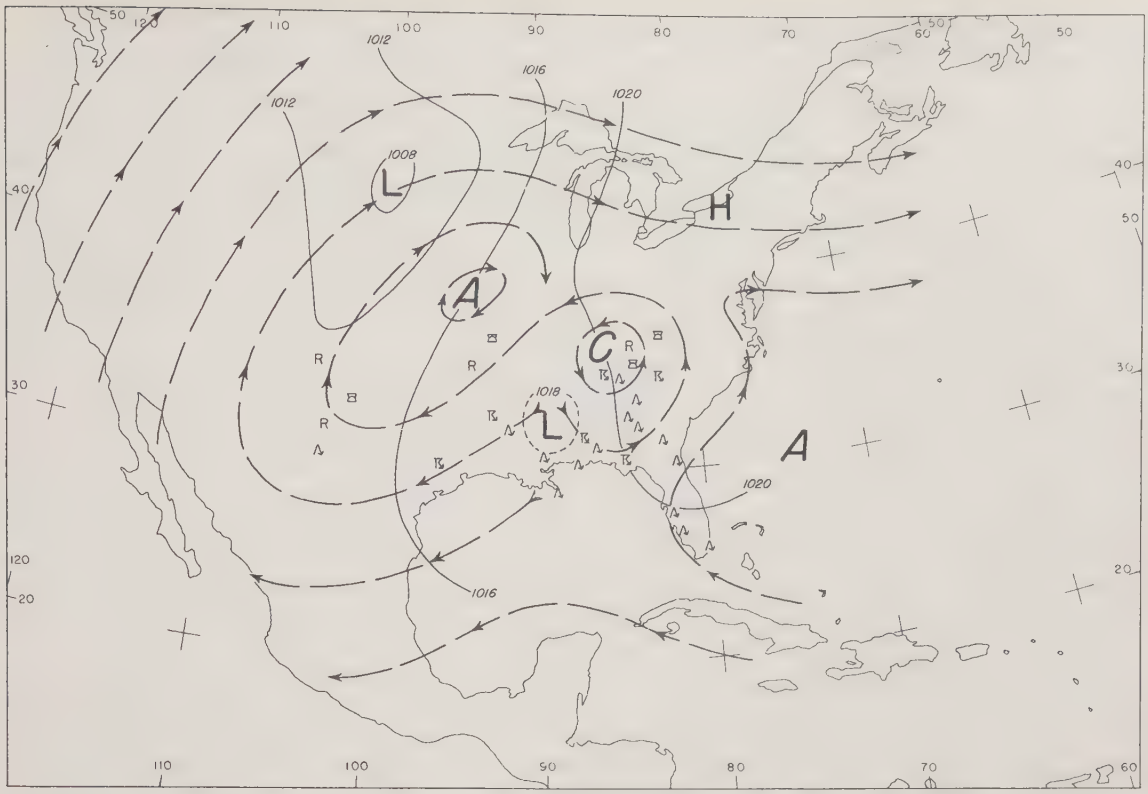

FIG. 15a.--Surface isobars, July 18, 1940, 1930 EST, and streamlines at 14,000 feet.

systems, however, especially on the eastern side, widespread thunderstorm activity continued. There, new air columns still kept moving into the zone of increasing cyclonic shear and curvature.

The area south of a center furnishes the greatest difficulty. Drying often takes place there corresponding to that described for the region south of the hurricanes (6). In the anticyclonic shearing zone between the westerlies south of the low and the tropical easterlies, subsidence develops. Moreover, there is a compensating effect for the convergence within the low. Not all the centers observed acted in accordance with this reasoning. Figure 15c, for instance, still indicates active convection near the coast, although the center itself had receded northward more than 200 miles as compared with the preceding day. The main anticyclonic shearing zone was quite close to the coast.

As in hurricane situations, a cyclonic deformation exists in the tropical easterlies south of a center This deformation is likely to travel westward as a wave in the easterlies and lose its connection with the low center farther north. Winds turned to southeast in southern Texas on July 19, 1940 (Fig. 15b), and stations farther west successively reported a shift to

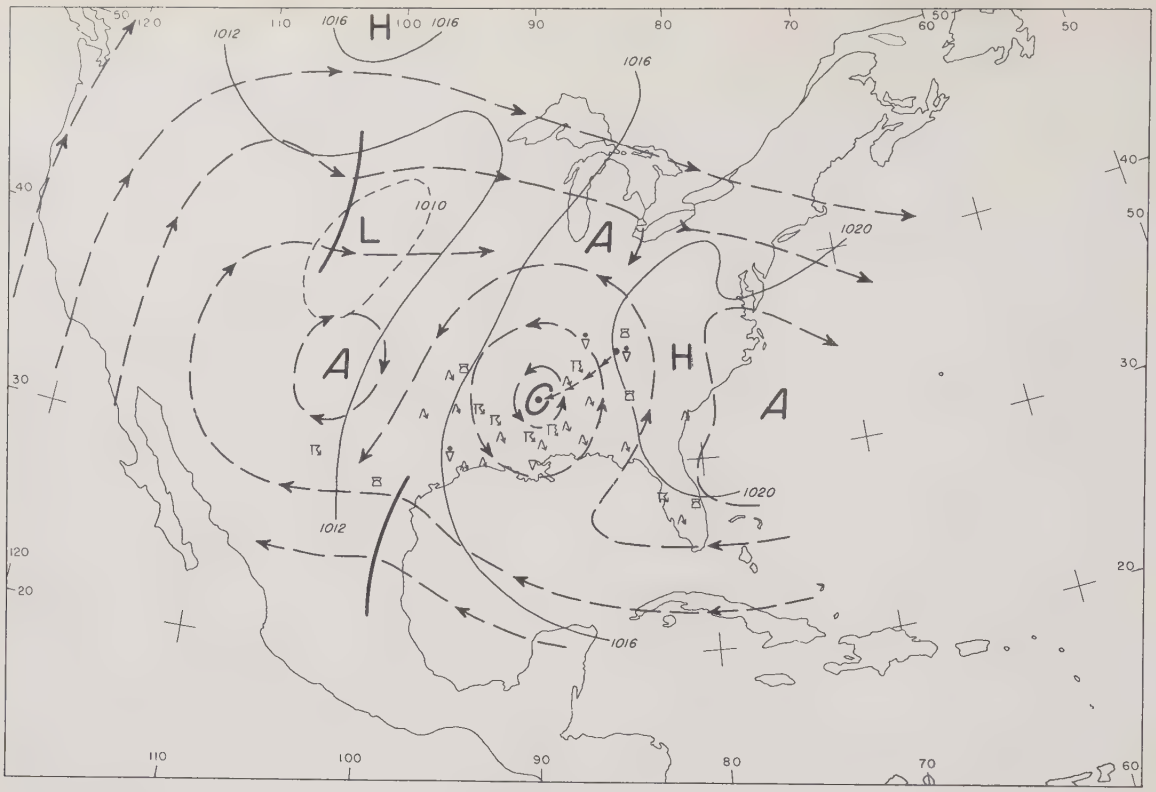

FIG. 15b.--Surface isobars, July 19, 1940, 1930 EST, and streamlines at 14,000 feet.

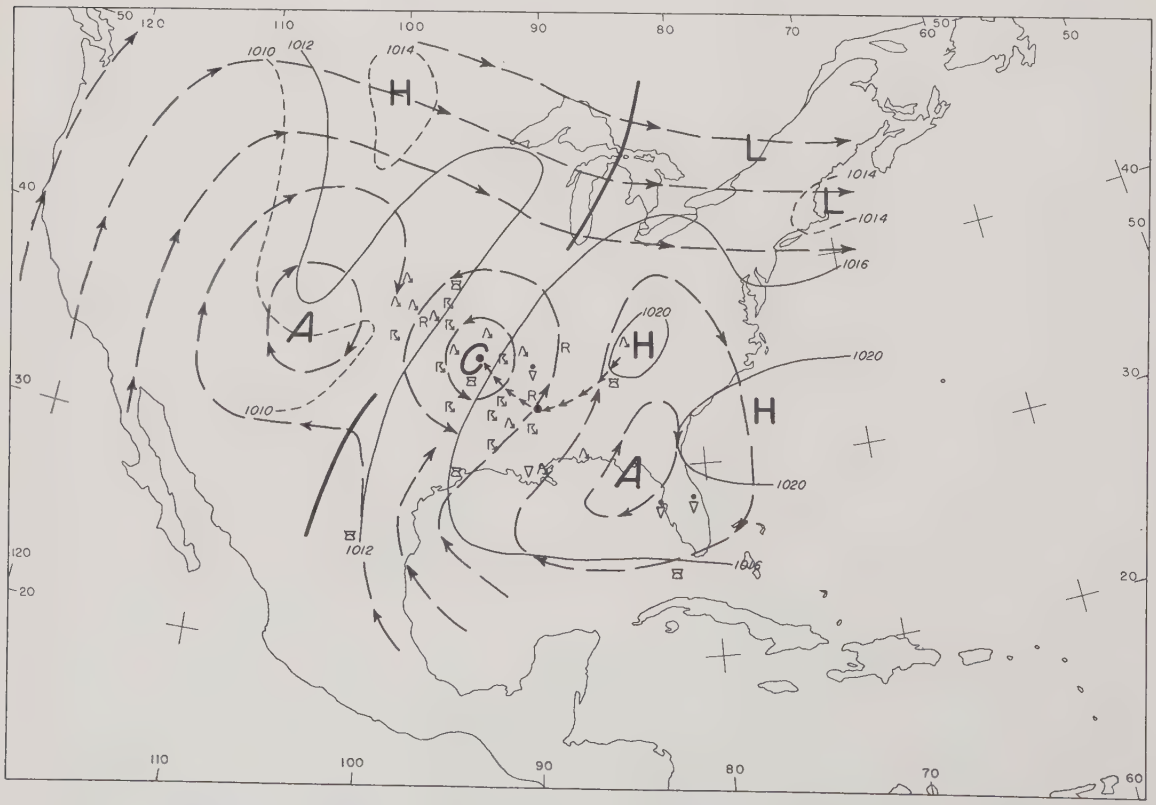

FIG. 15c.--Surface isobars, July 20, 1940, 1930 EST, and streamlines at 14,000 feet.

southeast. On July 20 the wave was very well marked in western Texas.

Even small low centers of but 100-200 miles diameter are always focal points of potential trouble. Especially the arrival of a fresh supply of colder air in the middle troposphere can cause the diameter to double and triple in just a few hours, with a rapid increase of the wind speed aloft. That happened twice. The upper low center illustrated in Figure 15 also widened greatly between July 19 and July 20, 1940. Thunderstorm activity spread, and there were reports of severe thunderstorms. At the same time the surface low center weakened and completely disappeared on July 20.

Clockwise rotation of all centers over the United States took place between July 18 and 20. Note the path of the low center. The West Atlantic high came in on the 20th, while the anticyclone initially located over Kansas split on the 19th. One part moved rapidly eastward and weakened. The other receded southwestward. On the 20th the familiar picture of four systems arranged about the subtropical col existed over the United States, except that the col area itself was occupied by the large upper low.

It was very difficult to speak of steering in this situation. The gradual clockwise rotation of the entire subtropical map pattern seemed to be the dominating feature. In several of the other situations, however, a pronounced zonal current that acted as steering current developed. A large increase in the strength of the northern westerlies caused some of the lows to be caught in the anticyclonic shearing zone. They were then dragged northeastward and weakened rapidly, at least until they established connection with the polar front. Two other centers drifted gradually westward from Texas as the easterlies over the United States maintained themselves.

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